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SYNTHESIZED CAD METHODS FOR COMBAT VEHICLE SURVIVABILITY ANALYSIS

PAUL H. DEITZ
THEODORE M. MUEHL
SCOTT L. HENRY
GARY S. MOSS
EDWIN O. DAVISSON
SUSAN A. COATES

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Paul H. Deitz, Theodore M. Muehl, Scott L. Henry,
Gary S. Moss, Edwin O. Davisson, Susan A. Coates

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To support its Army role in Vulnerability/Lethality analysis, the Ballistic Research Laboratory (BRL) has developed a suite of computer tools (called BRL-CAD) to assist in the generation, validation and interrogation of military geometry. Originally targeted to the support of vulnerability and nuclear survivability codes, these methods now also support many signature models, including some developed at TACOM/Keweenaw Research Center, Environmental Research Institute of Michigan (ERIM), Georgia Tech Research Institute, Northrop, and others. In this paper, the use of these tools is demonstrated. An Armored Fighting Vehicle (AFV) of the class being considered in the Armored Systems Modernization (ASM) program is used to show 1] how the input geometry is generated and 2] how various analysis codes are utilized in order to understand some of the performance issues affecting survivability. A candidate AFV is modeled geometrically and various images are generated to check the design. An estimate of system weight is performed. Next a series of ballistic vulnerability and signature computations are applied to the design, demonstrating the kinds of metrics which can be derived in an analysis cycle.

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SYNTHESIZED CAD METHODS FOR COMBAT VEHICLE SURVIVABILITY ANALYSIS

Dr. Paul H. Deitz, Mr. Theodore M. Muehl,
Mr. Scott L. Henry, Mr. Gary S. Moss,
Mr. Edwin O. Davisson and Ms. Susan A. Coates

Vulnerability/Lethality Division
US Army Ballistic Research Laboratory
ATTN: SLCBR-VL-V (P. Deitz)
Aberdeen Proving Ground, MD 21005-5066

ABSTRACT

Tomorrow's combat vehicles must be capable of meeting a significant number of design objectives, some of which may conflict one with another. In order to project the benefits and burdens of various design variants, modern computer methods are required to generate and analyze candidate designs quickly.

To support its Army role in Vulnerability/Lethality analysis, the Ballistic Research Laboratory (BRL) has developed a suite of computer tools (called BRL-CAD) to assist in the generation, validation and interrogation of military geometry. Originally targeted to the support of vulnerability and nuclear survivability codes, these methods now also support many signature models, including some developed at Tank Automotive Command (TACOM)/ Keweenaw Research Center, Environmental Research Institute of Michigan (ERIM), MITRE, University of Illinois and others.

In this paper, the use of these tools is demonstrated. An Armored Fighting Vehicle (AFV) of the class being considered in the Armored Systems Modernization (ASM) program is used to show 1] how the input geometry is generated and 2] how various analysis codes are utilized in order to understand some of the performance issues affecting survivability. A candidate AFV is modeled geometrically and various images are generated to check the design. An estimate of system weight is performed. Next a series of ballistic vulnerability and signature computations are applied to the design, demonstrating the kinds of metrics which can be derived in a diverse analysis cycle.

INTRODUCTION

Probably the highest priority program in the Army today is called the **A**rmored **S**ystems **M**odernization (**ASM**). Formerly called the **H**eavy **F**orces **M**odernization (**HFM**), its objective is to develop a coherent strategy for design, analysis, optimization and acquisition of the next generation **A**rmored **F**ighting **V**ehicles (**AFV**). Key issues which must be addressed concern how the mission roles underwritten by some 29 current systems will be supported in the future. To what degree should

commonality of chassis, turrets and other vehicle parts play a role? And what might be the benefits and burdens in both performance and cost if commonality were to be exploited?

Last year the HFM program began to examine the ramifications of design options for six principal AFVs. Each vehicle was "evolved" in a manner consistent with past practice in which individual systems are developed essentially as independent entities. Also a strategy was developed in which vehicles within similar weight classes shared common parts in an effort to gain advantages due to standardization. The **B**allistic **R**esearch **L**aboratory (**BRL**) participated in these efforts by providing vulnerability analyses of **1**] current baseline vehicles, 2] independently evolved vehicles, and 3] vehicles with commonality.

Following past practice, the Advanced Systems Concepts Division, Tank Automotive Command (TACOM), supplied the BRL with blueprints of each concept. With this guidance, the BRL generated solid model target descriptions. The descriptions, threat information provided by the Intelligence Community and other system data, were folded together to perform vulnerability analyses for each vehicle.

The approach used by the BRL to supply vulnerability support to the ASM program is probably the most familiar example of what is called *high-resolution, item-level modeling.* In this brand of modeling, three-dimensional target geometry is generated and then linked to an application code. The BRL has developed a substantial suite of software dedicated to the task of generating three-dimensional target geometry and the means to link it to vulnerability analyses. However this strategy is widely extensible to many other item-level analysis models.

In this paper we seek to make the following points:

- To achieve the challenging objectives of the ASM program, many design tradeoffs will have to be performed in an accurate and timely fashion.
- Many of the analytic tools needed by the ASM program currently exist.
- Only through the use of tools like those illustrated in this paper, will it be possible to achieve the necessary accuracy and timeliness.
- Important "economies-of-scale" accrue when target geometry is shared and upgraded as required by an expanding set of application codes.

Although these analytical methods have been described previously, this is the first time that a single system, here an early candidate for the **F**uture **I**nfantry **F**ighting **V**ehicle (**FIFV**) will have been used to illustrate all analyses using the same target geometry.

In the next section, the general analysis strategy used in this paper will be described. Next, some of the design objectives for the FIFV will be listed. The target geometry will then be generated, viewed, and subjected to group of item-level analyses. Finally, some advanced analyses, appropriate to mature system designs, will be discussed.

ANALYSIS STRATEGY

The strategy used in the subsequent analyses can be summarized in the following steps:

Step 1]: Generate Concept Geometry— First a mathematical file is generated which describes the three-dimensional concept vehicle which is to be analyzed. This process will be described below.

Step 2]: Link Material/Attribute Files— In this step, material properties associated with various vehicle parts are linked to the geometry assembled in the previous step. The material properties required depend on the applications codes to be run; examples of such properties are hardness, conductivity, density, reflectivity, etc.

Step 3]: Exercise Application Codes— Having prepared the necessary input, the concept vehicle is linked in turn to the application codes needed to examine the utility of a given design. Typical examples of such codes are [1-3]:

- Weights & Moments-of-Inertia
- Vulnerability/Lethality Codes
- Neutron Transport Code
- Optical Images
- Bistatic Laser Designation
- Infrared Modeling

- Radar Modeling
- Acoustic Modal Predictions
- High-Energy Laser Damage
- High-Power Microwave Damage
- Structural/Stress Analyses
- X-Ray Simulation

Step 4]: Compare Predictions with Requirements— In this step results of the analyses are compared with the system requirements. The potential suitability of the concept design *vis-a-vis* the system requirements is first revealed here.

Step 5]: Modify Vehicle Configuration— Based on the assessments performed in **Step 4**] the system configuration may have to be altered. The changes may impact geometry and/or material properties as performed in **Steps 1**] and **2**].

Step 6]: Repeat Steps 3] & 4]— This loop may actually be performed many times as various design options are examined. It will also have to be performed as the system detail is refined as the process evolves.

FIFV DESIGN OBJECTIVES

In order to understand how vehicle design arises from a set of specifications, we give the following examples taken freely from the ASM **O**perational and **O**rganizational (**O&O**) Plan [4] describing the FIFV requirements:

- Provide an Advanced Infantry Fighting vehicle with systems which will move, protect and offer fire support to dismounted infantry.
- Have sufficient firepower to defeat enemy infantry fighting vehicles and other enemy materiel.
- Provide protection for both the squad and crew against anti-armor munitions.
- System weight not to exceed 33 tons; be capable of swimming.
- Utilize front-engine chassis and provide rear egress for the squad.
- Provide minimal optical, infra-red and radar signatures.

Based on such system specifications, a designer develops a concept. The mechanics of converting that concept to a robust computer representation are discussed in the following two sections.

OVERVIEW OF BRL-CAD

The BRL has been involved with the generation and use of three-dimensional solid geometry for more than twenty years. Solid geometric modeling is a robust form of mathematical representation in which three dimensional forms are fully specified both from a geometric and material standpoint. The surfaces of objects are completely defined and interior material specified. This modeling is not to be confused with 2-1/2 dimensional or wireframe modeling which is actually an automated drafting process. Although the generation of blueprints is greatly enhanced, surfaces, materials, etc., are not defined and the analyses discussed in this article cannot be directly supported.

Some years ago the BRL embarked on an in-house program to generate a set of solid-geometry modeling tools focused especially on the task of high-resolution weapons modeling. Described extensively elsewhere [5-7], their capabilities are briefly summarized here:

- BRL-CAD is composed of more than 200,000 lines of source code which support:
  - □ Solid geometric editor (mged)
  - □ Ray tracing utilities
  - □ Lighting models
  - □ Many image-handling, data-comparison, and other supporting utilities
- Geometrical representations supported by BRL-CAD include:
  - □ The original **C**onstructive **S**olid **G**eometry (**CSG**) BRL data base
  - □ **N**on-**U**niform **R**ational **B**-**S**pline Surfaces (**NURBS**)
  - □ The faceted data representation (PATCH) developed by Falcon/Denver Research Institute and used by the Navy and Air Force for vulnerability calculations.
- It supports association of material (and other attribute properties) with geometry which is critical to subsequent applications codes.
- It supports a set of extensible interfaces by means of which geometry (and attribute data) are passed to applications:

- □ Ray casting
- □ Topological representation
- □ 3-D Surface Mesh Generation
- □ 3-D Volume Mesh Generation
- □ Analytic (Homogeneous Spline) representation

- Source code for BRL-CAD has been distributed to more than 650 computer sites world wide including Government, Industry and Academia.

- In addition to the vulnerability and signature codes generated by the BRL, many other applications codes are supported including applications developed by workers at TACOM/ Keweenaw Research Center, ERIM, Northrop, MITRE, University of Illinois and scores of other sites.

GENERATING A TARGET DESCRIPTION

As noted above, based on the O&O plan and other system constraints/specifications, the vehicle concepter generates an initial design. In the Advanced Systems Concepts Division, TACOM, that step has been actualized through the generation of blueprints in which the initial design is committed to paper. That procedure continues today though with the aid of CAD hardware/software which automates the process. The computer files generated in that procedure are of the 2-1/2 D, wireframe, class discussed in the **OVERVIEW** above and thus cannot be used directly for the item-level models to be illustrated here. The practice has therefore been for target describers at the BRL or elsewhere to utilize the TACOM-generated blueprints together with the BRL-CAD solid-model editor, *mged,* and generate a solid-model target description. For the FIFV vehicle being illustrated here, that task represents approximately three man-weeks of effort. It is also worth noting that the "FIFV" being used to illustrate these methods is ***not*** the system configuration currently being pursued by the ASM program; rather it was a design suggested by the U.S. Army Infantry School,† committed to blue prints by the Advanced Systems Concepts Division, TACOM, but later discarded in favor of another design.

† The conceptual drawings of this Infantry Fighting Vehicle and related data were released to the BRL for use in this medium in a Memorandum dated 26 February 1990, authorized by Mr. Roger K. Halle, Acting Chief, Advanced Systems Concepts Division, TACOM.

The process of generating the FIFV solid-model description is illustrated in Figs. 1-5. Figure 1 shows the wire-frame prompting when using the *mged* editor. The center image shows the geometry file in its entirety. The target geometry is arranged in a hierarchical tree structure with various (sub)levels of geometry. The three subordinate levels to the top tree level are shown around the margins and are composed of Hull, Turret and Suspension. Figure 2 shows the subtree for the Turret only. This level has subtrees composed of Turret.ext, Main.gun and Ammo. Insight into the tree structure is given by Fig. 3. The top of the subtree starts with the Turret.ext. Below it are the various subelements and so on. This organization structure supports any mix of English and numerical naming conventions. Through various *mged* commands any subsets of system geometry can be displayed interactively and modified. At the bottom-most levels are found the basic building blocks used in the solid geometry modeling strategy. Those basic shapes, called primitives, can be combined into complex structures and then edited (scaled, rotated, translated) as integrated entities.

Figure 4 shows the geometric subtree, Hull, at the center surrounded by its subtrees, Hull.ext, Crew and Hull.ammo. Figure 5 shows the last major subtree, Suspension. In the margins are the subtree elements to Suspension, Track.link.1, idler.wheel and Roadwheel. Note only individual track links, road and idler wheels are shown. A powerful command supported by *mged* is the ***instancing*** feature. Through this command a single part can be replicated to many different locations throughout the vehicle space. Thus the complete track in the suspension system is composed of many copies of the single illustrated track link. In addition to conserving file storage resources, this feature makes possible fast changes in design simply by replacing the instanced copy. For example, if a number of road wheels, each of different shape, were to be used in a radar-scattering study, numerous target descriptions could be generated based on substituting a single copied wheel.

In addition to the generation of the geometry shown in these figures, it is necessary to associate material properties to the various geometric parts.

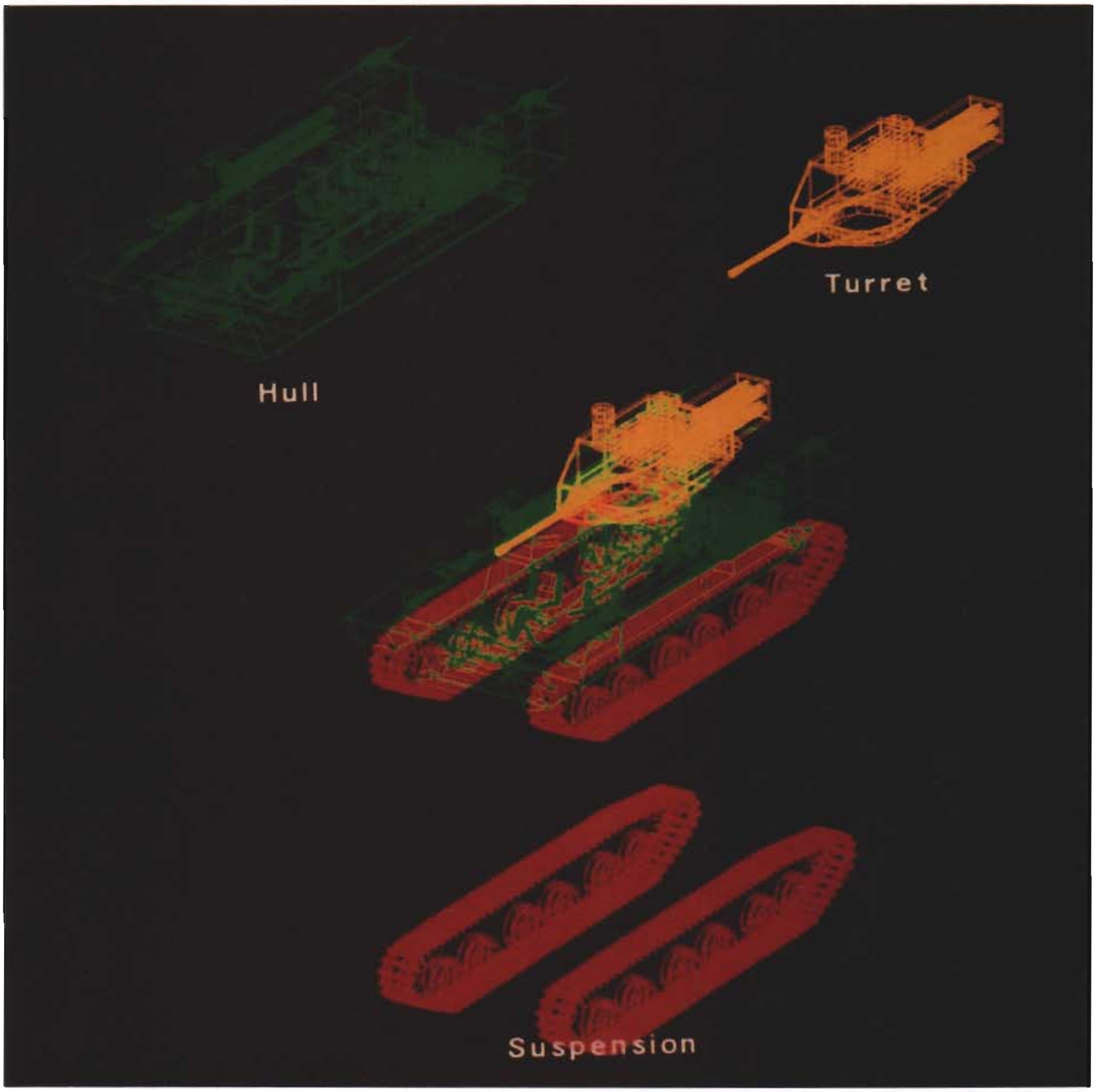


Figure 1. Wireframe view of Future Infantry Fighting Vehicle (FIFV) geometry as presented by the BRL-CAD solid geometry editor, *mged*. Center image shows the total system geometry. The file structure is hierarchical, with the major systems Hull, Turret and Suspension constituting the first subdirectories in this structure.

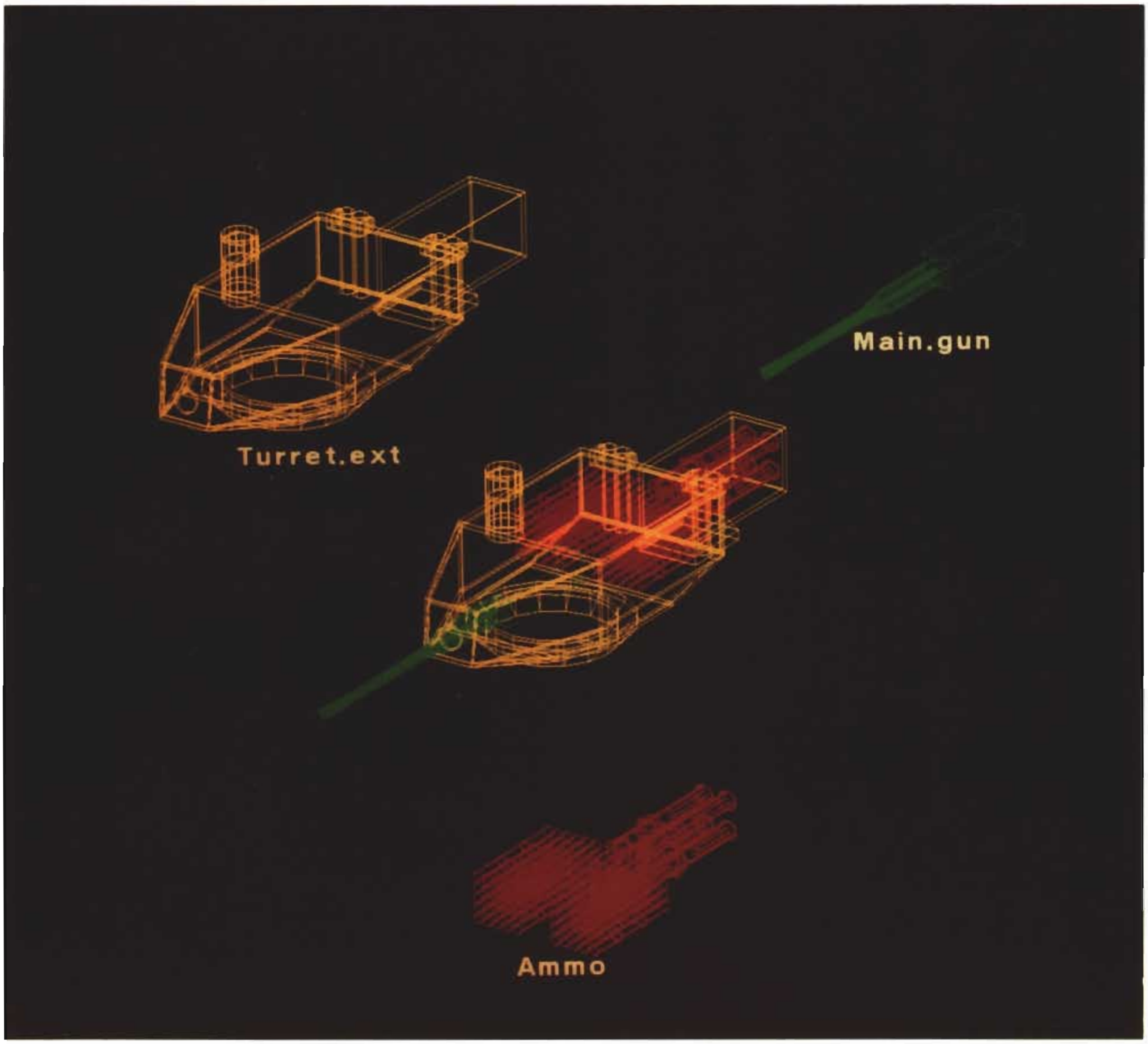


Figure 2. Wireframe *mged* image of the FIFV subsystem, Turret, shown in the center with the associated subdirectories Turret.ext, Main.gun and Ammo.

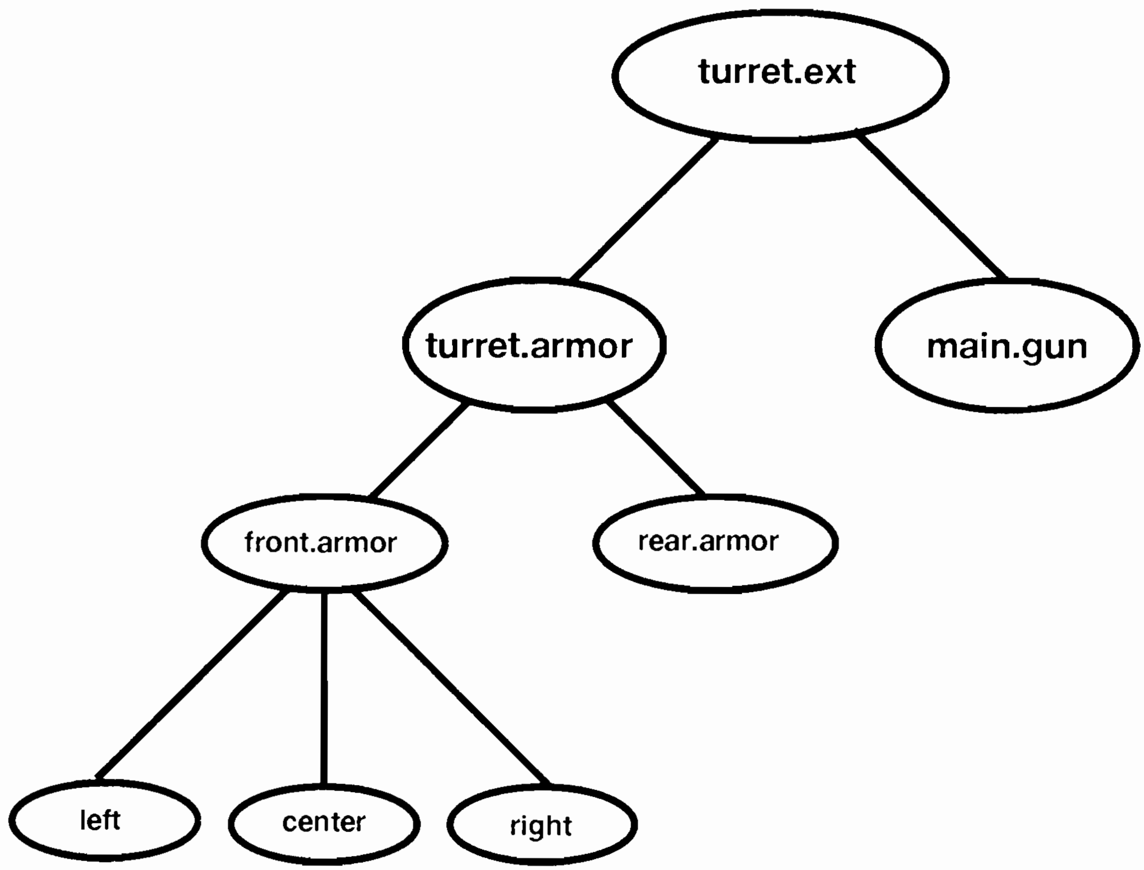


Figure 3. Illustration of the hierarchical data structure used in *mged* editor. Shown here is the subtree for the Turret.ext and below. Such a structure makes possible logical groups of vehicle parts including natural English naming conventions. Editing operations (rotation, scaling, translation) can be applied at any level of the tree structure.

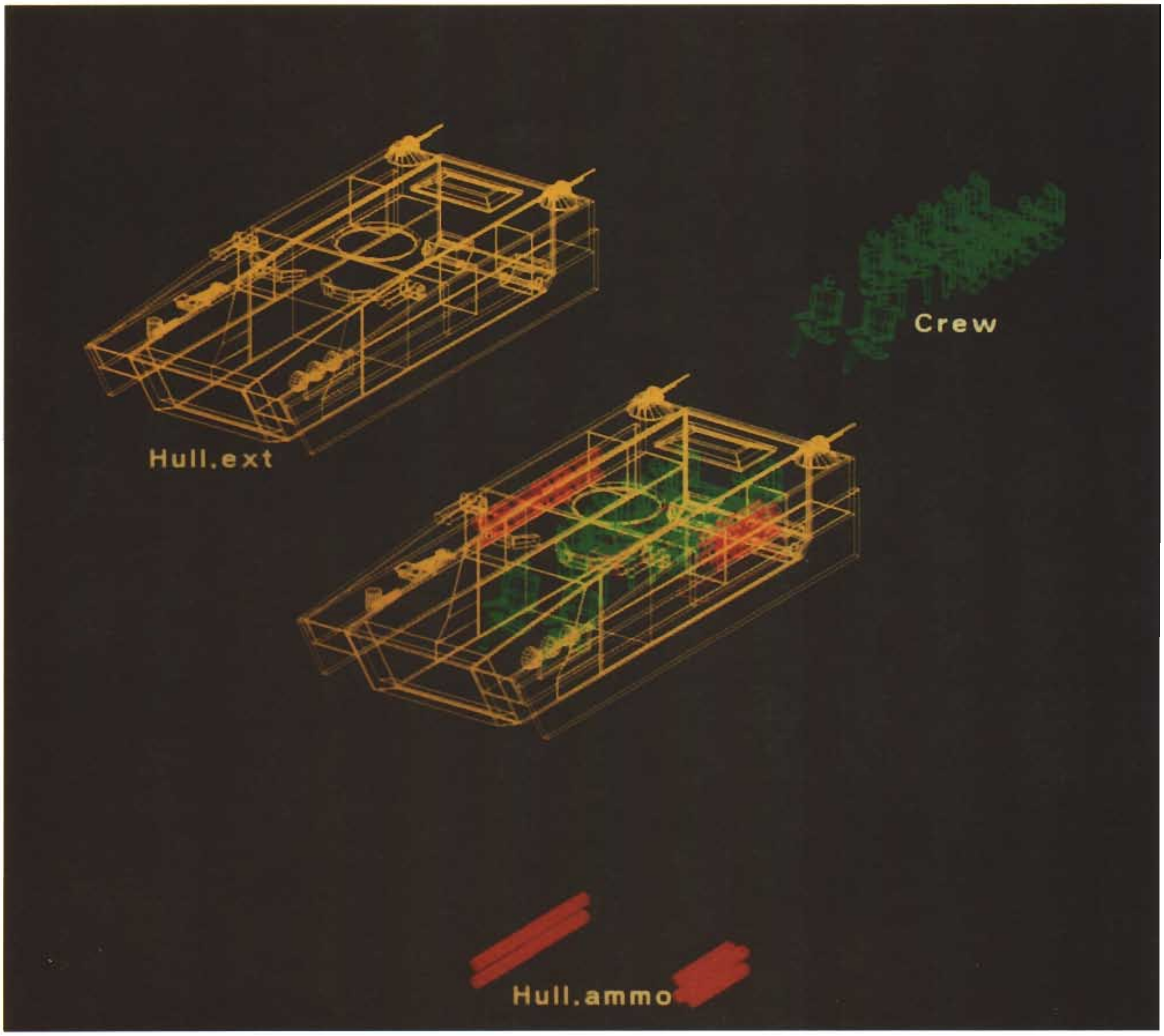


Figure 4. Wireframe *mged* image of the FIFV subsystem, Hull, shown in the center with the associated subdirectories Hull.ext, Crew and Hull.ammo.

Figure 5. Wireframe *mged* image of the FIFV subsystem, Suspension, shown in the center with the associated reference parts Track.link.1, Idler.wheel and Roadwheel. These parts are copied and referenced to multiple points in space to compose particular structures. By changing a referenced part (*i.e.* reshaping a road wheel), a composite collection of such parts can be changed quickly.

In the steps which follow, both geometric and material information is passed to a suite of application codes.

RAYTRACING GEOMETRY

In this section we describe the principal method used to connect geometric/material information to the various analytic models. In the **OVERVIEW** above appeared a list of interfaces. The first and by far the most exploited method of linkage is through raytracing. For BRL the paradigm was natural as the original uses of solid modeling were for vulnerability and neutron-transport studies. Thus shotlines could be used to traverse a warhead trajectory, warhead fragment or neutron path. Raycasting will be used for the applications described below.

Figure 6 shows a large number of raytrace histories developed from the FIFV target description. A four-inch grid structure was set up using the BRL-CAD tools; it can be seen in the right foreground. Rays were fired through each grid intersection through the vehicle geometry. At every point along a ray the vehicle part and material makeup is known. This information can be used to generate color displays. In Fig. 6, certain portions of the geometry are printed so that a sense of vehicle composition can be gained simply by viewing the ray information.

Such data are critical to performing warhead penetration studies. In addition to defining material properties at any point along a ray, the raycasting tools support the computation of surface normals and surface curvature at each material boundary along the shot line. These tools are interactive and can be tied to complex physical algorithms in tightly coupled computation loops.

Some of the applications supported by raycasting methods are listed in Fig. 6. It is important to note, however, that ray casting is only one of a number of methods to link geometry/material to applications. Of particular note is the link through faceted or 3-D Surface Mesh geometry.

A significant number of applications codes particularly in the area of signatures have been designed *ab initio* for support by geometry constructed uniformly of closed polygonal facets. Given such geometry, the application codes typically call for a series of numerical integrals over a collection of facets. In the past few years, the Survivability Division, TACOM, has developed significant code extensions [8, 9] with which BRL-CAD target geometry can be translated into a pure faceted form. By means of this strategy the large body of target descriptions generated in BRL-CAD format can now be applied to facet-based codes. This greatly enhances the utility of the Infrared PRISM™ code developed by Keweenaw Research Center and TACOM, as well as electromagnetic signature codes generated by Georgia Tech Research Center, Northrop and others.

OPTICAL RENDERING

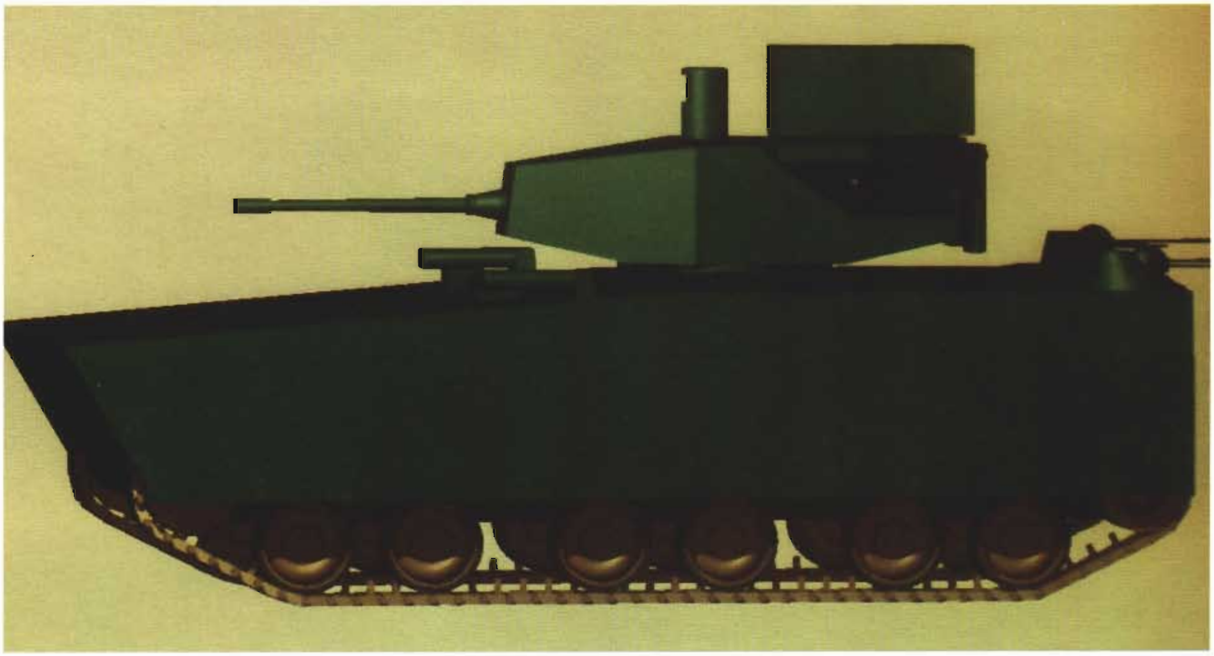
The BRL-CAD tools contains two powerful optical lighting models. Some of their features will now be illustrated. Figure 7 shows two standard images derived with the FIFV geometry. Above is a standard image from the vehicle left side, with normal opaque material properties assigned to the geometric entities. Below, a cutaway view has been generated by passing a plane through vehicle geometry and removing geometry between the cutting plane and the viewing position. This is one means of looking into interior vehicle space.

Another lighting-model option is shown in Fig. 8. Here the armor has been given the properties of transparent glass. With a small amount of optical backscatter assigned to the transparent regions, the viewer can peer through the vehicle exterior to view the placement of interior components.

Yet another lighting-model option is shown in Fig. 9. This simulation supports a calculation in which a forward observer illuminates a target as in the Copperhead weapon system. The orientations of the viewing and illuminating positions with respect to the target are completely arbitrary; also many different surface scattering properties (*i.e.* mixtures of diffuse and specular scattering) can be assigned to the vehicle surface to cover many kinds of battlefield conditions.

Through another lighting-model feature, an overhead optical sensor can be simulated viewing the FIFV for different positions of solar illumination. A ground plane has been placed beneath the vehicle; it is being viewed from an angle of (-30°, 45°). Shown in Fig. 10, four solar positions are computed for angles (top-left to bottom-right) of (90°, 20°), (90°, 45°), (-90°, 45°) and (-90°, 20°), respectively. Such computations are useful, for

Figure 6. Method of raytracing vehicle geometry. A 4" x 4" grid is shown to the right. A ray is fired through each grid intersection through the vehicle geometry. As the ray traverses the file, the ray history (hit points, surface normals, material properties) is recorded. It can be displayed as shown here or passed on to various application codes for post processing.



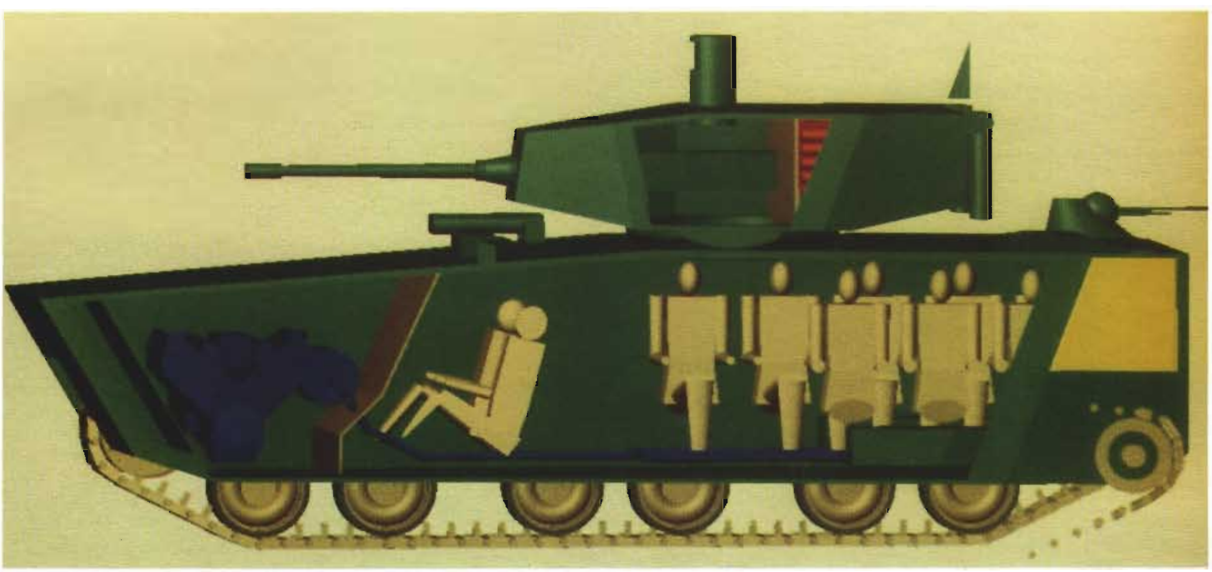


Figure 7. Use of the BRL-CAD lighting modeling to view the finished FIFV geometry. From a viewing angle of (82^{o}, 3^{o}) (azimuth, elevation), the upper image shows the exterior of the vehicle. Below is a cutaway from the same perspective. A slicing plane has been passed through the geometry to remove material between the plane and the viewing position.

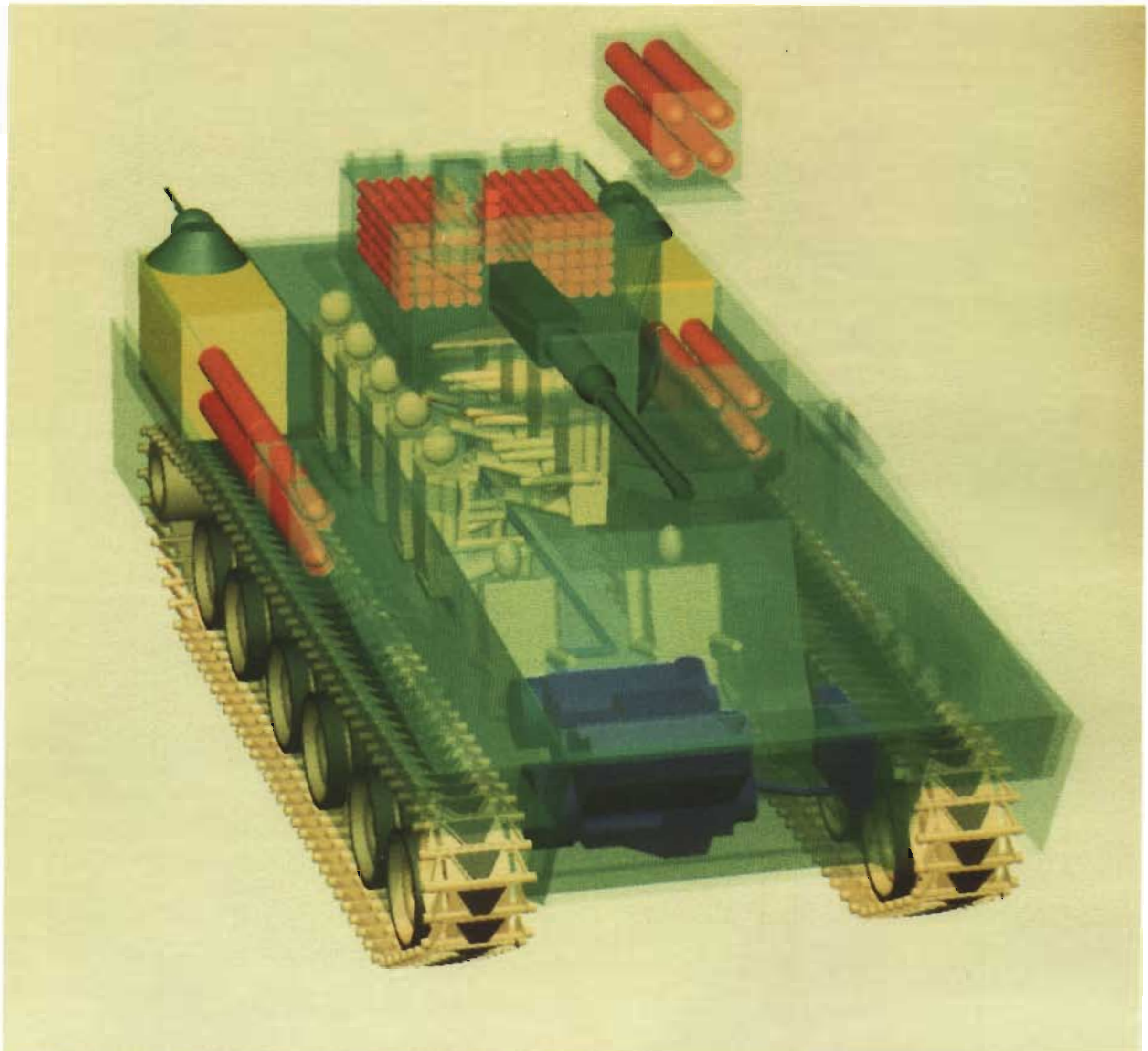


Figure 8. Transparent rendering (-15°, 20°) of the FIFV. A lighting model option allows armor to be rendered transparent, revealing internal component placement.

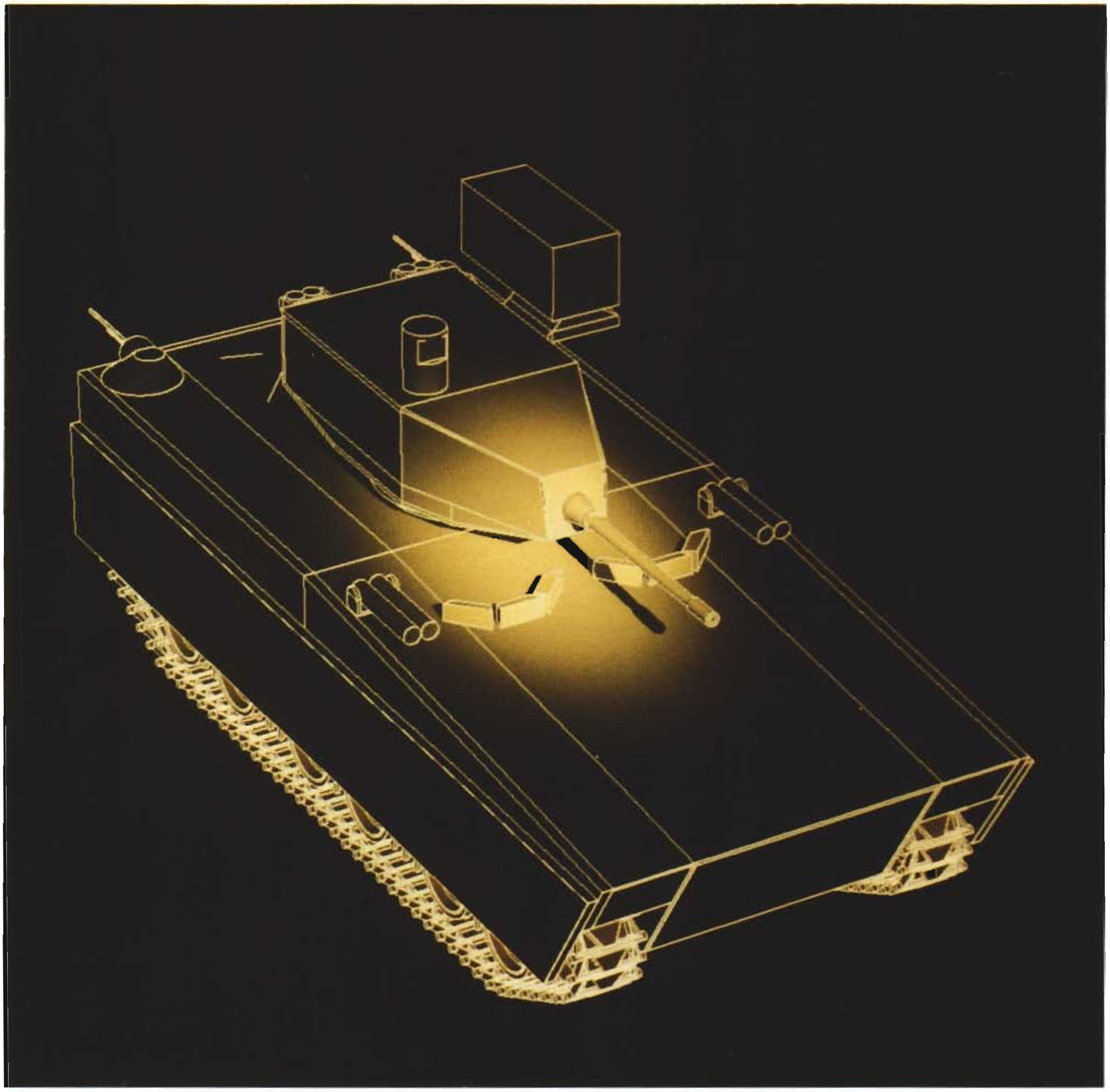


Figure 9. Simulation of a laser designator on the FIFV. Using the BRL bistatic lighting model, any target surface condition or viewer/illumination orientations can be used. The viewing angle is (-30°, 30°); the designator is directed from (-10°, 30°).

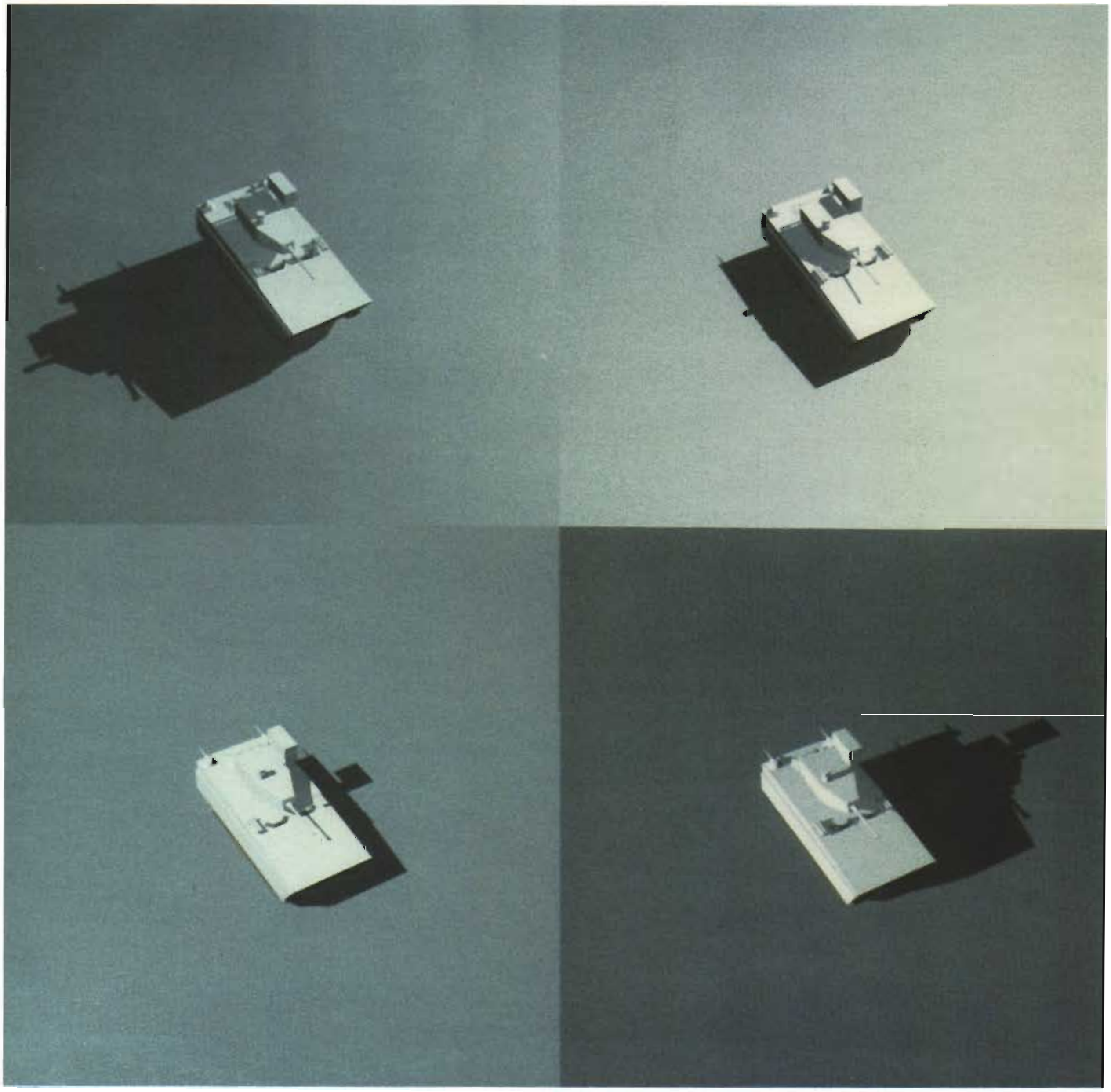


Figure 10. View of FIFV for different positions of solar illumination. A ground plane has been placed beneath the vehicle; it is being viewed from an angle of (-30°, 45°). Four solar positions are computed for angles (top-left to bottom-right) of (90°, 20°), (90°, 45°), (-90°, 45°) and (-90°, 20°), respectively.

example, in studies of **A**utomatic **T**arget **R**ecognition (**ATR**), in particular the effect of ground shadows on target detection and/or recognition.

The limiting effects of sensor noise and resolution can be added easily to the simulation illustrated in Fig. 10. Figure 11, upper-left, shows a noise-free image. Both multiplicative and additive noise has been added to the same image to give the next result, upper-right. The lower-right and lower-left views show a two-stage process of spatial low-pass filtering which have the effect of reducing the resolution. Such processing is useful for examining the utility of sensor systems as a function of performance parameters.

MASS PROPERTIES

The calculation of mass properties emerges naturally from a solid-modeling framework. As noted earlier, material properties are associated with geometry in the target description phase. To make mass properties calculations, material densities are linked to each geometric entity. Using a dense raycasting scheme such as that illustrated in Fig. 6, it is a straight forward numerical procedure to sum the vehicle parts to estimate weights. This can be accomplished on any subsets of geometry as defined by the tree-structure organization.

A weight budget for the FIFV for geometry *not* modeled in this concept design is listed in Table I. Since a concept model is not complete, it is important in any initial mass computations to account for future geometry not yet modeled. Such a budget can then be combined with weight estimates from the modeled target to form final projections.

Figure 12 gives such a projection. In the upper part of the figure, the weight projection is given as a composition of four sources. The hull and turret geometries modeled and not modeled (from Table I). They appear to agree nicely with the target weight proportions as supplied by the Advanced Systems Concepts Division, TACOM.

Using a similar computation strategy as above, centers-of-mass and moments- and products-of-inertia estimates can be made as well. Figure 13 illustrates a center-of-mass calculation. Three cylinders have been added to the target geometry to illustrate the location of the calculated center-of-mass. This has been displayed using the transparent lighting model option.

Moments- and products-of-inertia are important for assessing overturning moments for the vehicle during such activities as gun firing and rough-terrain traversal. They also can come into play when, for example, the affect of up-armoring a turret is being examined in the context of servo-drive design.

VULNERABILITY ESTIMATES

The ability to support vulnerability/ lethality estimates has been central to the development of the BRL-CAD modeling tools. There are many vulnerability modeling tools [10, 11] available based both on target class (e.g. aircraft, heavy tank, APC) as well as application. Uses range from first estimates of concept vehicle protection levels to detailed calculation of spare parts requirements and repair times.

For an early ASM assessment, a first-cut vulnerability analysis is appropriate in which protection levels for the vehicle are assessed as well as the standard mobility and firepower metrics. Figure 14 illustrates these vulnerability computations. Three kinds of results are shown, each for frontal (0°, 0°) and left-side (90°, 0°) shots. At the top, perforation information is plotted for a particular anti-armor threat. Using armor penetration equations, a shot is fired on a 4" x 4" grid. Either perforation/no-perforation information can be plotted or the magnitude of residual penetration can be plotted on a color scale. The former is plotted here together with a graphing feature which begins with a standard optical image of the target. Over that is a line plot which gives the projections of the major underlying vehicle regions; finally the vulnerability cell data are overlayed. This procedure enhances the ability to interpret vulnerability data in the context of vehicle layout.

Illustrated in the middle of Fig. 14 is the standard Mobility/Firepower metric. This is normally read as Mobility or Firepower (M or F), and computationally is the larger of the two independently derived (M, F) values. We point out that these metrics are normally referred to as Mobility and Firepower *Losses-of-Function* as they are strictly *not* probabilities [10]. Nevertheless, they

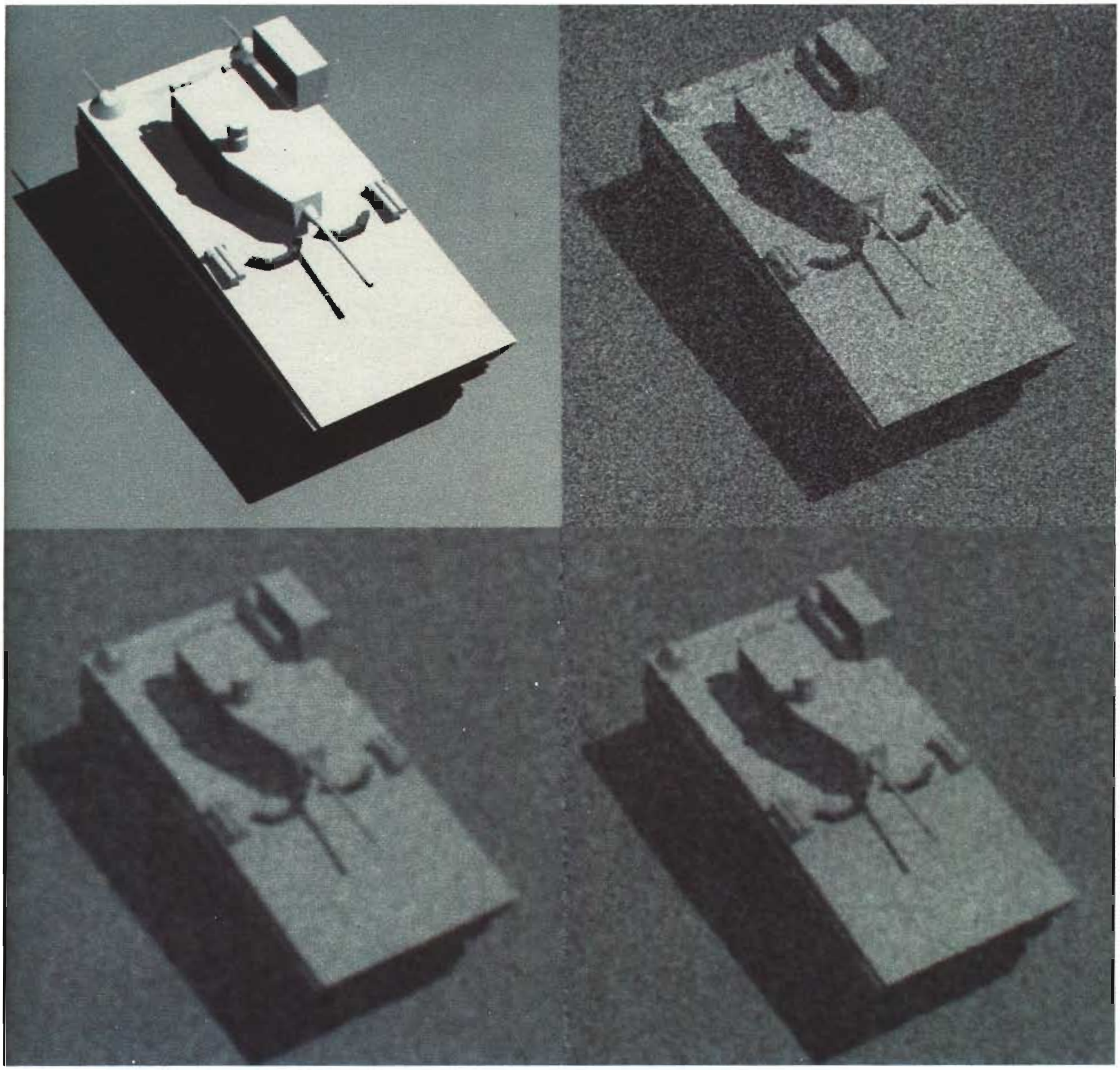


Figure 11. Overhead view of FIFV showing effects sensor noise and resolution. Upper-left image is noise-free. Multiplicative and additive noise have been added to the same image to give the next result, upper-right. The lower-right and lower-left views show a two-stage process of spatial low-pass filtering which have the effect of reducing the resolution.

Table I. Weight budget for the FIFV for those items not modeled during the initial concept design phase.

Electrical (Hull & Turret)		400 lbs
STINGRAY		1200 lbs
Displays (Computer, etc.)		200 lbs
Crew/Squad (OVE, seats, water, etc.)		3545 lbs
Compartmentalization Materiel		2000 lbs
Machine Gun Ammo (3600 rnds)		270 lbs
Main Gun Ammo (160 rnds)		1320 lbs
Active Protection Devices		20000 lbs
	TOTAL	10935 lbs

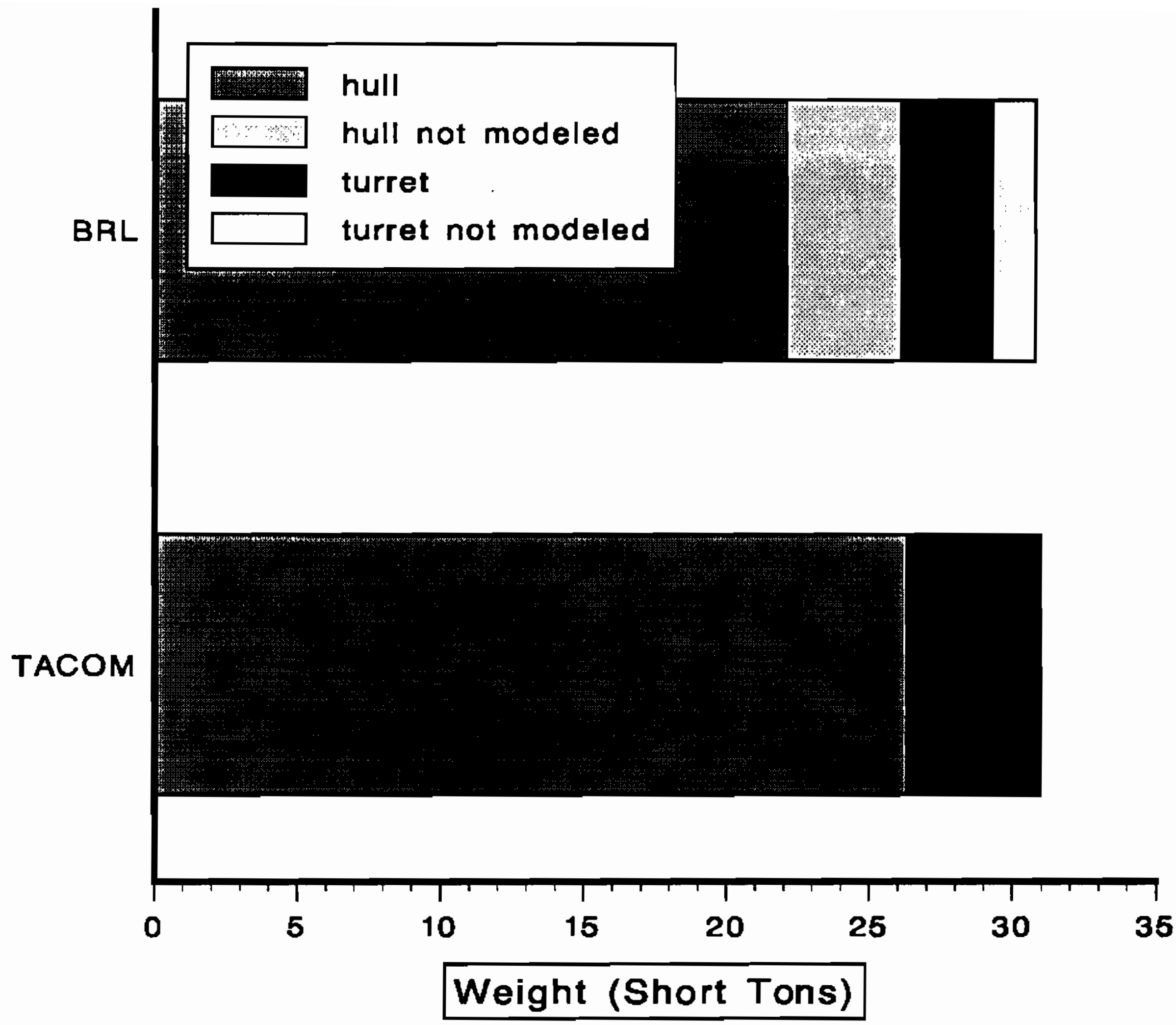


Figure 12. Breakout of weight budget based on BRL methods (above) and TACOM target values. The BRL-CAD tools have been used to make estimates for the concept geometry. The estimates for both the hull and turret are combined with the budgets for items not yet modeled to achieve estimate of total system weight.

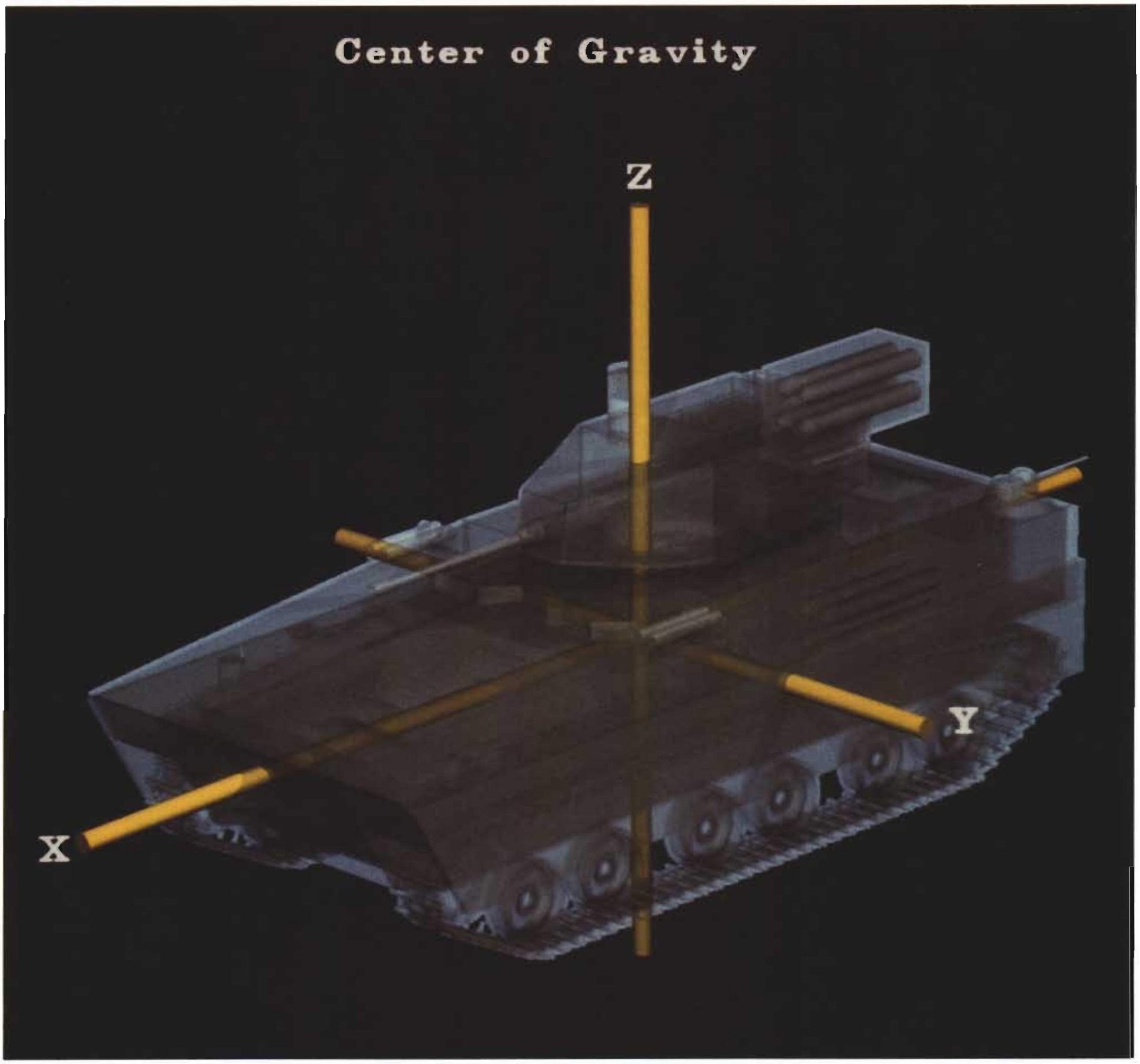


Figure 13. Illustration of center-of-mass calculation. Three cylinders have been added to the target geometry to illustrate the calculated center-of-mass. The transparent lighting model option is used as well. With similar methods, moments- and products-of-inertia can be calculated as well.

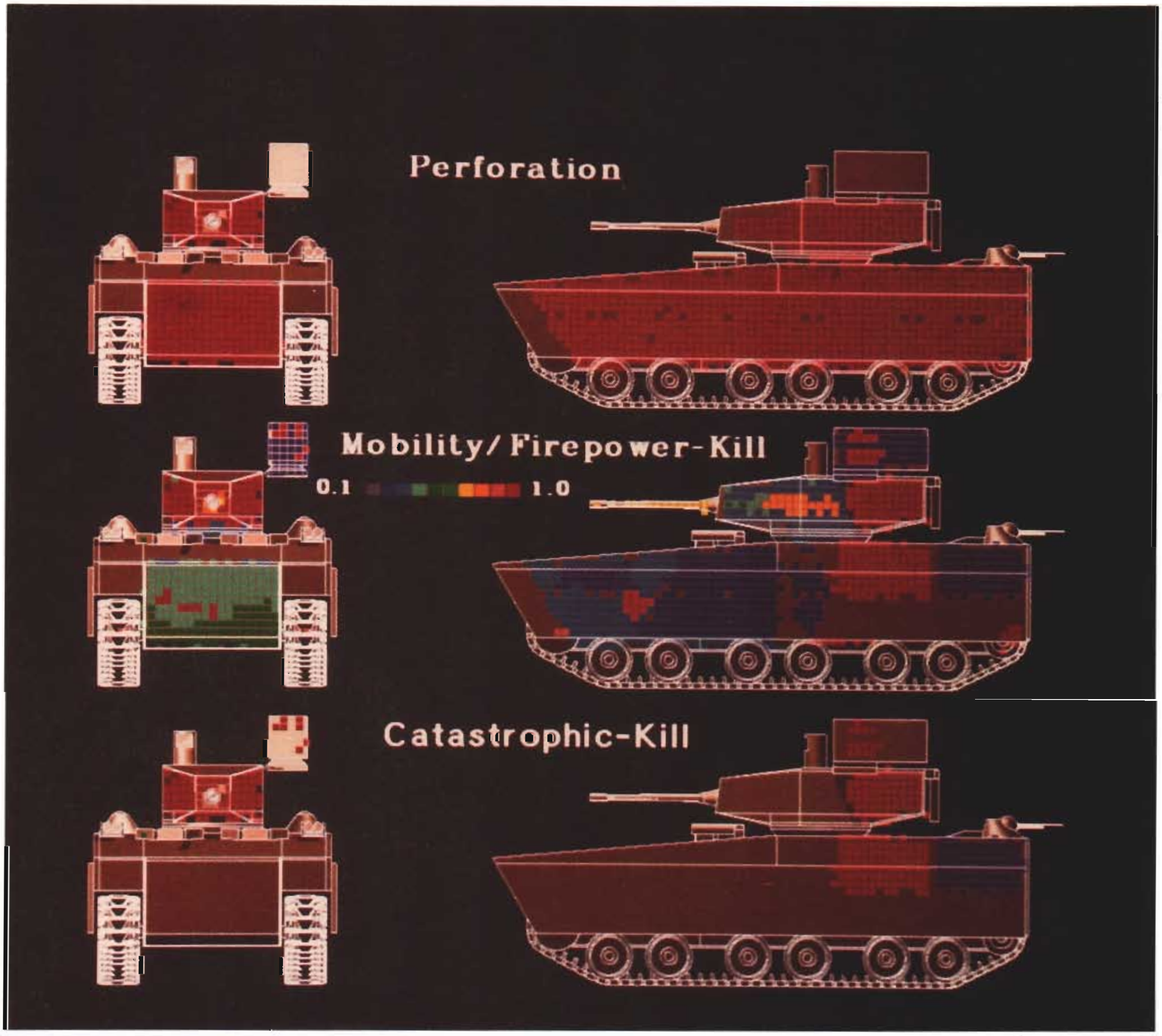


Figure 14. Standard cell plot used to display various estimates obtained from vulnerability analyses. Two views of the vehicle are shown: 0 and 90 degrees attack azimuth, 0 degrees elevation. From each of the views, a 4" x 4" grid is superimposed on the target geometry. A single shot is fired into each cell. Optional outputs include a] Perforation (with residual penetration) [top], b] Probability of Mobility or Firepower Kill (M/F Kill) [middle] and c] Probability of Catastrophic Kill (P of K-Kill) [bottom].

are often referred to as "PKs" in the working vernacular.

The bottom image pair in Fig. 14 gives the Catastrophic Kill probabilities for the FIFV. These results are true probabilities that the vehicle will be utterly destroyed through explosion or fire or otherwise be uneconomically repairable.

TOPOLOGY EXTRACTION

Particularly in the area of radar signatures, the exterior shape of a vehicle strongly controls the direction and magnitude of energy scattering. In an early effort to lend support to radar scattering codes which are based on scattering from idealized representations of vehicle geometry (*e.g.* plates, dihedrals, trihedrals), the BRL developed a filter program which traverses the surface of a vehicle and extracts the subset composed entirely of flat plates. The coordinates of the plates can then be handed off to the radar program. Figure 15 shows the results of processsing the FIFV with the plates program. The subsets of the vehicle surface topology which are flat have been turned into colored panels.

In similar fashion, a related program looks for the orthogonal intersection of flat plates pair-wise in order to back out dihedral elements. This dihedral calculation for the FIFV is displayed in Fig. 16. The tan elements indicate the location of the dihedral structures.

RADAR MODELING

The BRL currently utilizes a number of analytical tools to understand the scattering of radar waves from ground vehicles. The first technique to be discussed is based on a variant of the lighting model described earlier. This method is particularly applicable to high-frequency radar simulations ($\geq$ 90 Ghz) in which the scattering closely approximates geometrical scattering of optical waves. To simulate the performance of a scanning radar, we refer to Fig. 17. This image shows the FIFV vehicle as seen by the radar which will be used to scan the surface with a six-inch resolving spot. Using the BRL-CAD lighting model, the FIFV is given optical reflection characteristics which are nearly 100% reflecting; in addition, only a single light source is used located at the position of the viewer (monostatic configuration). The upper image of Fig. 18 shows a high-resolution result of the calculation. The bright image points show all order returns (numbers of ray bounces) for energy which leaves the single source and returns to the viewer; *i.e.* a bright spot can indicate a single bounce, in which case the surface normal at the spot is pointed directly back to the viewer. Or the surface geometry may be such that two bounces are encountered (*e.g.* dihedrals), or any higher number of reflections. By a related analysis program the ray history for such an image can be examined to see the contribution of various levels of multiple bounce. The lower image is calculated by convolving a six-inch aperture over the upper image. This brings the resolution down to that of a scanning radar.

Such diagnostic calculations are valuable design tools. They can prompt a vehicle designer concerning basic surface shaping strategies and point the way to reducing high-return scattering centers. This calculation is also efficient using today's workstation technology, and such images can be computed in a few minutes. These images have been shown to correlate strongly with field data [12, 13] and are particularly important for the future battlefield in which resolving radars will play in increasingly important role.

A more rigorous form of radar calculation will be described next. Historically radars were used to infer target range and closing rates. For the early radars, a figure of merit, the radar cross section, was of key importance, as it represents the efficiency with which radar waves are scattered back to the receiver. Certain modern radars, when placed on moving platforms such as aircraft, can be used to form a two-dimensional image of targets. Radar imagery of this class is called **S**ynthetic **A**perture **R**adar (**SAR**). The FIFV has been analyzed with a SAR program [14], and the results are shown in Figs. 19-22. Figure 19 shows the FIFV as seen by the SAR radar from a (35°, 30°) orientation. A horizontal flight path (left to right) is assumed. The properties of SAR processing are such that following signal detection and manipulation an image is derived which resolves the target in range and cross-range (along the flight path) but not in the remaining orthogonal direction. Thus the final SAR image orientation is similar to the optical rendering shown in Fig. 20.

A pair of SAR images for the FIFV is shown in Fig. 21 for a transmit Vertical, receive Vertical polarization mode. The upper image has been computed in a high-resolution mode (about 0.7-inch

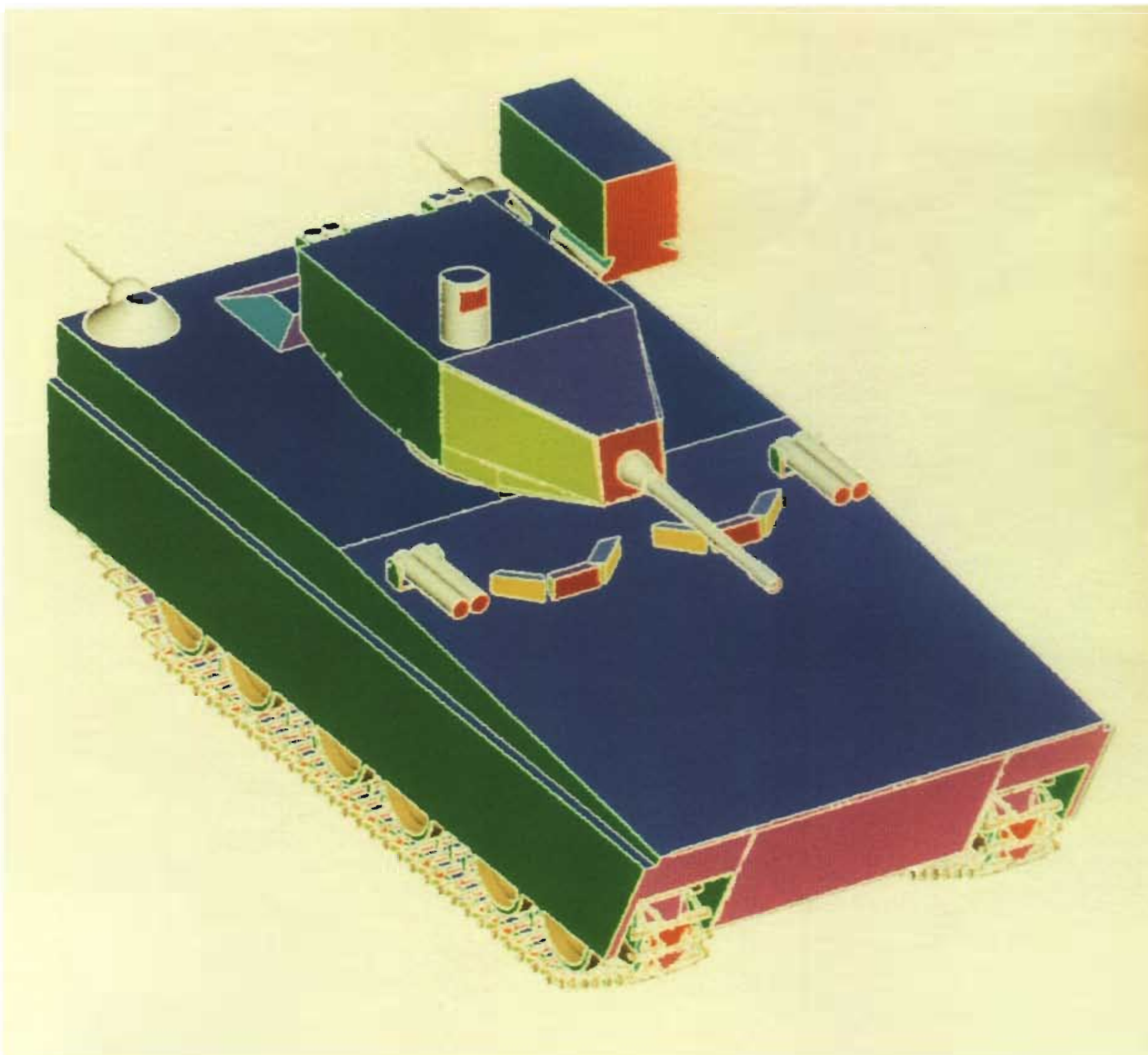


Figure 15. Image of FIFV showing those portions of the exterior composed of flat plates. The flat sections are shown in color (where the color is a function of the surface-normal direction) and can be handed off to radar-processing program.

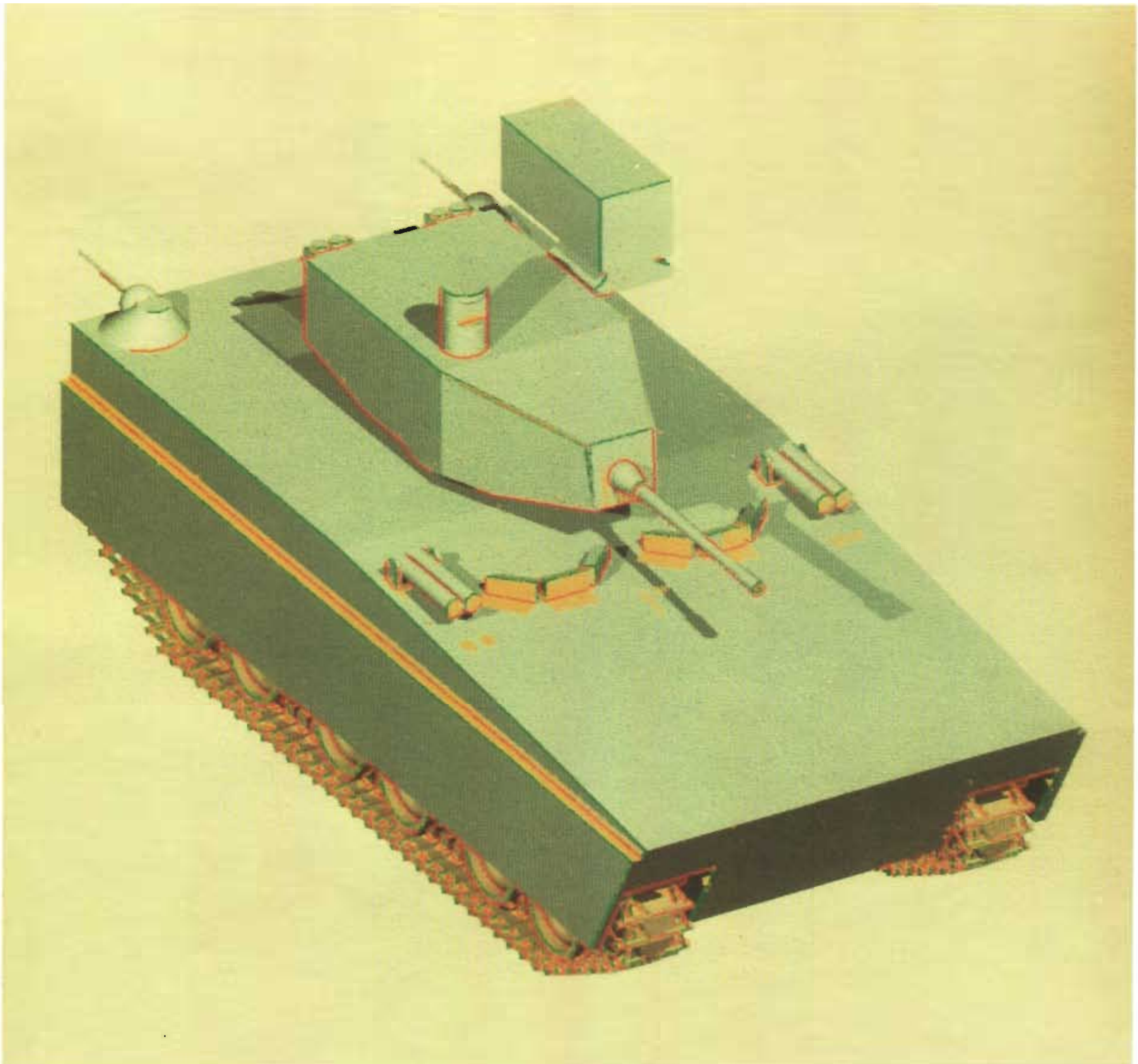


Figure 16. The surface topology of the FIFV has been processed to find adjacent orthogonal (*i.e.* dihedral) elements. Green lines indicate open dihedrals (concave), red lines indicate closed dihedrals (convex), yellow lines indicate orthogonal target elements adjacent in viewing space, but actually disconnected along the line-of-sight (disjoint). Tan areas show an approximation to the extent of concave dihedral elements. These elements can also be handed off to radar-processing programs.

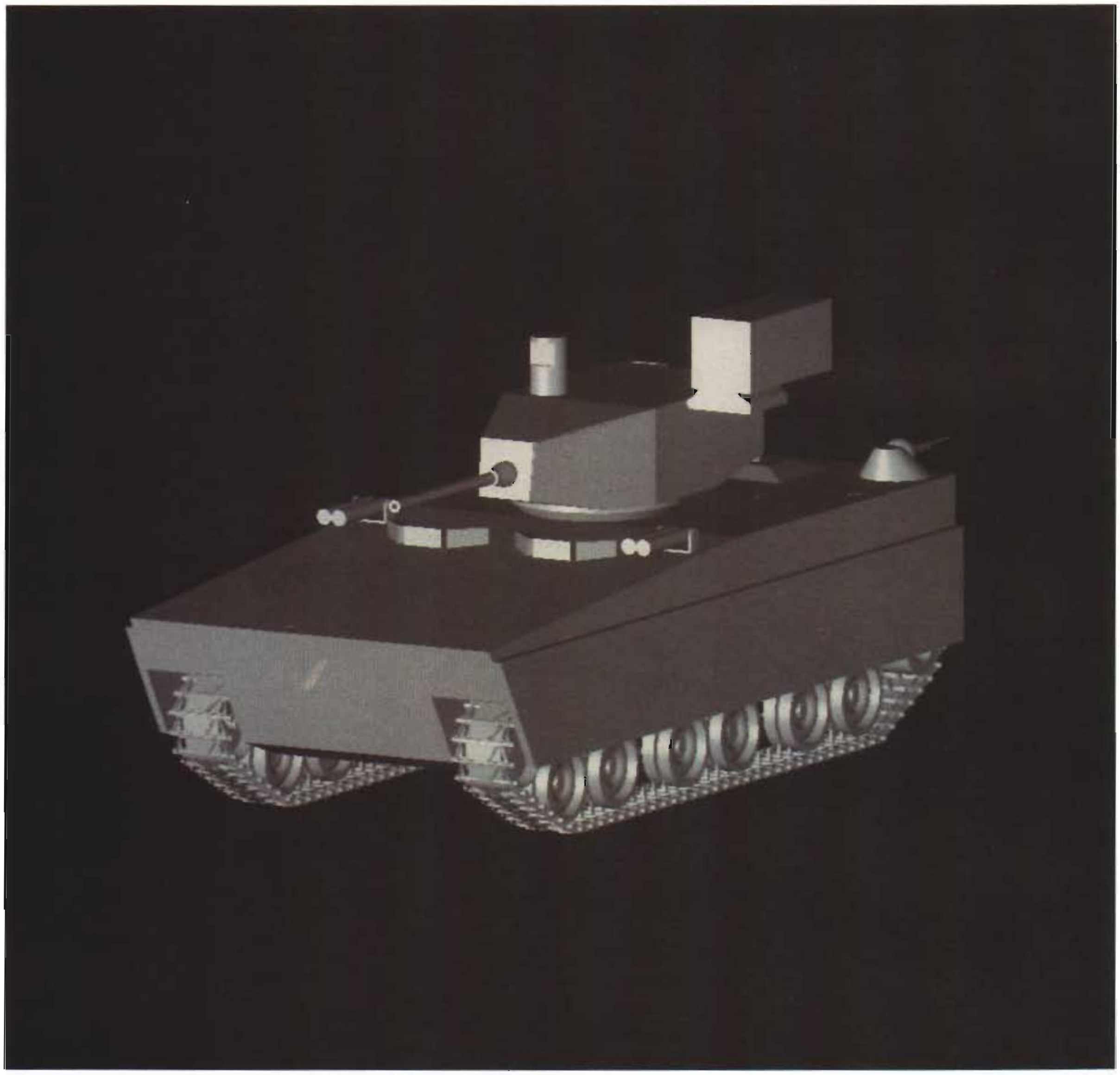


Figure 17. Viewing position (30°, 10°) for scanning radar simulation. Shown is standard optical image of FIFV.

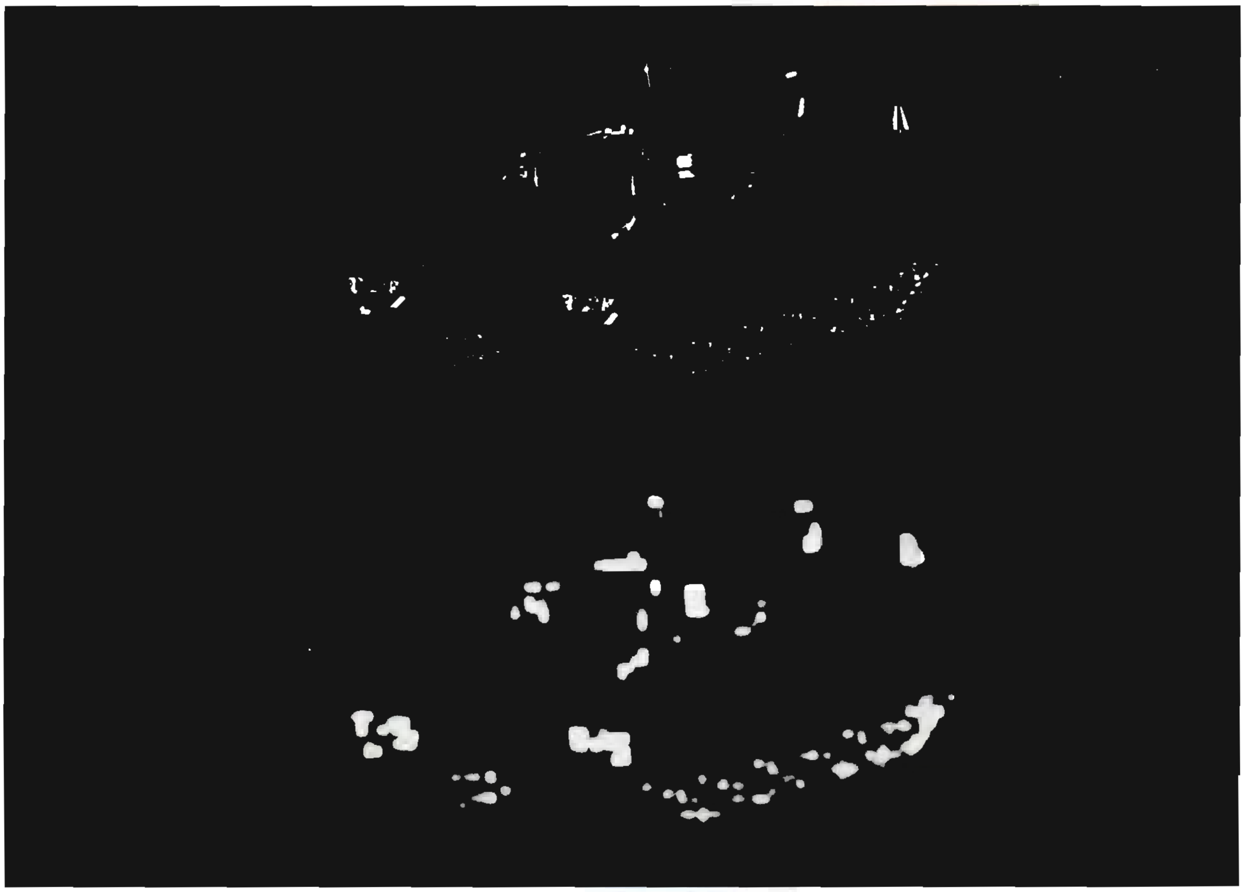


Figure 18. Result of optical lighting model used to simulate a high-resolution scanning radar; perspective same as Fig. 17 (30°, 10°). Target is given high specular scattering (mirror-like) properties. A single light source is directed from viewer towards target (mono-static configuration). Upper figure gives high resolution image; lower gives image with typical reduced resolution. Method supports true multiple-bounce capability.

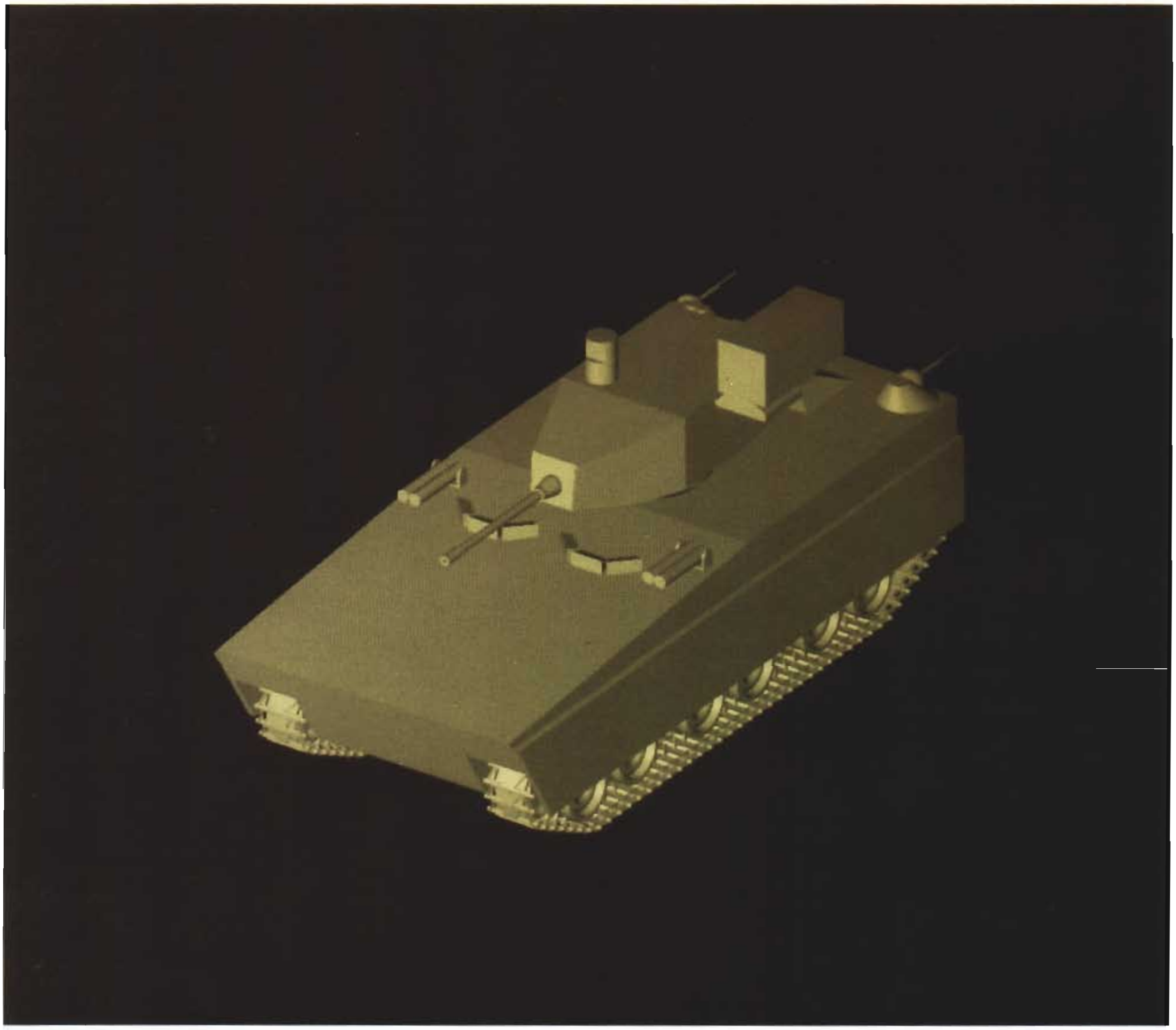


Figure 19. Optical image of the FIFV illustrating the radar view of the target (35°, 30°) for a synthetic aperture radar (SAR) simulation. The SAR is modeled as moving in the azimuthal direction (elevation and range constant).

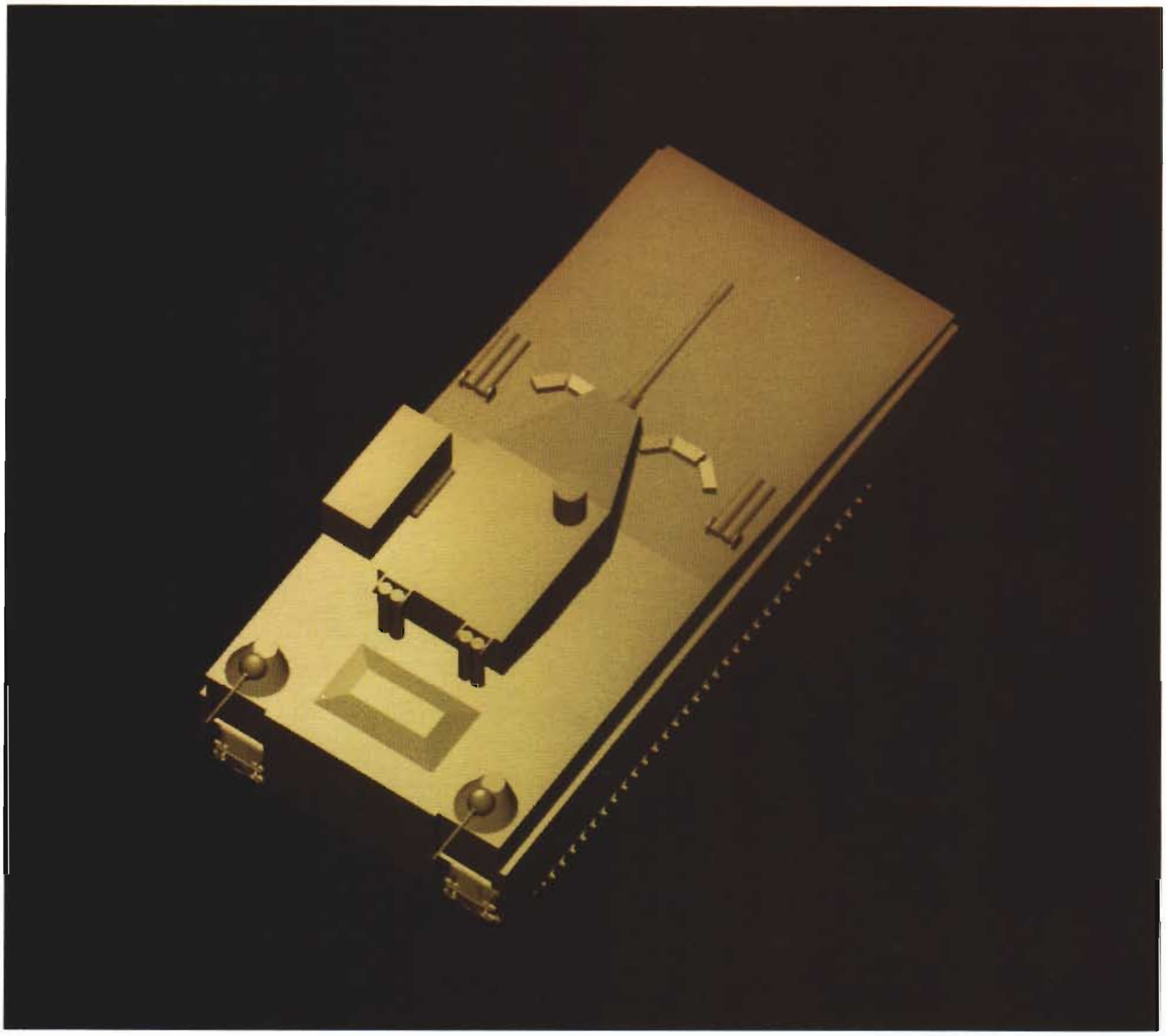


Figure 20. Complementary optical image to that shown in Fig. 19; the apparent aspect is $(215^\circ, 60^\circ)$ and is suggestive of the SAR reconstructive process when range is plotted against cross-range as in Figs. 21 and 22.

Figure 21. Computed SAR image for 10 Ghz, Vertical/ Vertical (co-polarization transmit/ receive modes). Upper image gives (unrealistic) resolution of 0.7 inches on target; lower image shows resolution of 10 inches.

resolution) and has not been constrained by practical frequency or coherence considerations of realizable radar systems. The lower image simulates a target resolution of 10 inches. In each of these images, the radar signal is propagating from top down. Range information is plotted along the ordinate and cross-range data along the abscissa. Figure 22 shows similar image pairs for the Vertical/Horizontal polarization mode.

ADVANCED APPLICATIONS

In the spirit of the emerging ASM program, the emphasis in this paper has been the analysis of concept armored systems. Clearly at the early stages of design much detail is yet unspecified, so more advanced forms of analysis must be delayed until the advanced design is performed. If the decision is made to proceed with vehicle design, many more detailed systems assessments can be performed.

In the area of vulnerability, some of the advanced applications include:

- Vulnerability reduction studies
- Estimates for spare parts and repair times
- Live-Fire predictions and vulnerability model calibration

In order to appreciate the evolutionary path that the FIFV program may take if it ultimately proceeds to a fielded system, we show two images of the Bradley Fighting Vehicle, the vehicle the FIFV would replace. Figure 23 shows the exterior view of the Bradley which has been modeled in very high detail to support various signature studies. The high interior detail is shown in the transparent armor mode in Fig. 24. This geometry has been used to support spare parts estimates, vulnerability reduction studies and the high-resolution vulnerability estimates for the Bradley Live-Fire program.

SUMMARY

In this paper we have reviewed the techniques of high-resolution, item-level modeling and how they can be applied to the Army's ASM program; emphasis has been placed on the analysis of concepts as the ASM program is still in a relatively formative stage of development.

It should be kept in mind that the applications illustrated here represent only some of calculations that can be exercised with geometry at the concept level. And as noted above, as the level of detail increases, more advanced applications can be brought to bear on issues of increasing complexity.

In many ways the costs of performing these analyses is coming down. Although it is still expensive to generate solid geometry, through use of the interactive tools illustrated, the process can be accomplished in a fraction of the time needed when previously such tasks were accomplished by hand. Also, because solid geometry is necessarily being applied much more widely than simply to vulnerability analyses as other important performance criteria relating to survivability emerge, there are significant economies-of-scale that accrue as target descriptions are recycled through a suite of analysis codes. In the end the Army most certainly cannot afford *not* to pursue these analysis strategies because it simply cannot risk developing materiel without benefit of the insights and guidance that the proper exercise of these tools can provide.

It is natural to expect that the growth in the power of these tools, the diversity of applications, and the ability to pass and share geometry across the analysis community will continue with significant influence on the outcome of the ASM.

However from both practical and theoretical perspectives, the most difficult analytic issue to be faced by the ASM program, or indeed any other weapons acquisition, relates to the absence of a quantitative framework capable of judging the suitability of a future armored vehicle to perform in a future battlefield or even rank-ordering a set of candidates! To state it in another way, the methods illustrated in this paper form a strategy for estimating individual measures-of-performance; *i.e.* these methods give estimates of ballistic protection, weight, optical, IR and radar detection probabilities, etc. They tell us nothing, however, about the *optimal mix* of system performance parameters which may lead to optimum or even ranked *measures-of-effectiveness* in the battlefield. This issue surfaced as well five years ago [15] during seminal **A**rmored **F**amily of **V**ehicles (**AFV**) program.

Given the lethality of the future battlefield together with the weight and volume constraints placed on future armored systems, it is more clear

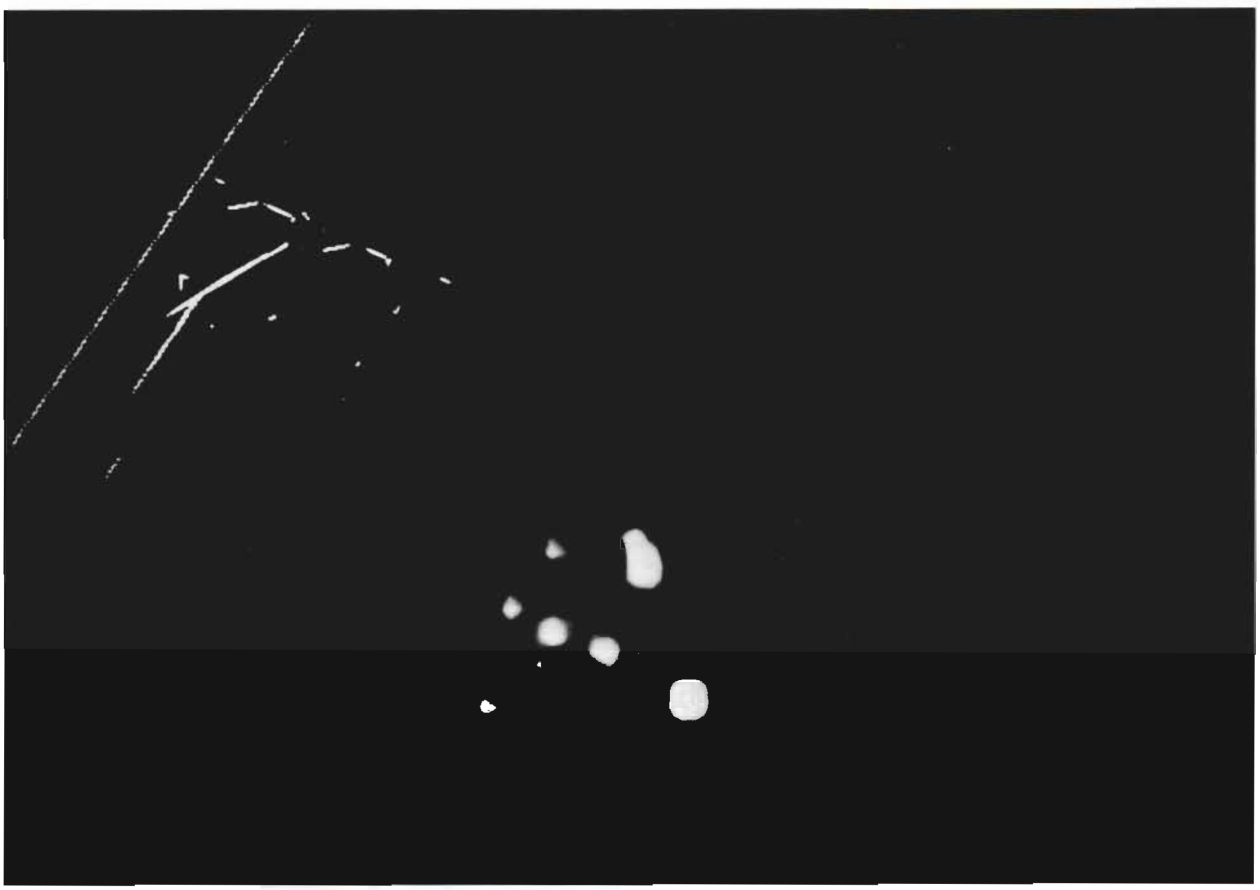


Figure 22. Computed SAR image for 10 Ghz, Vertical/ Horizontal (cross-polarization transmit/ receive modes). Upper image gives (unrealistic) resolution of 0.7 inches on target; lower image shows resolution of 10 inches.

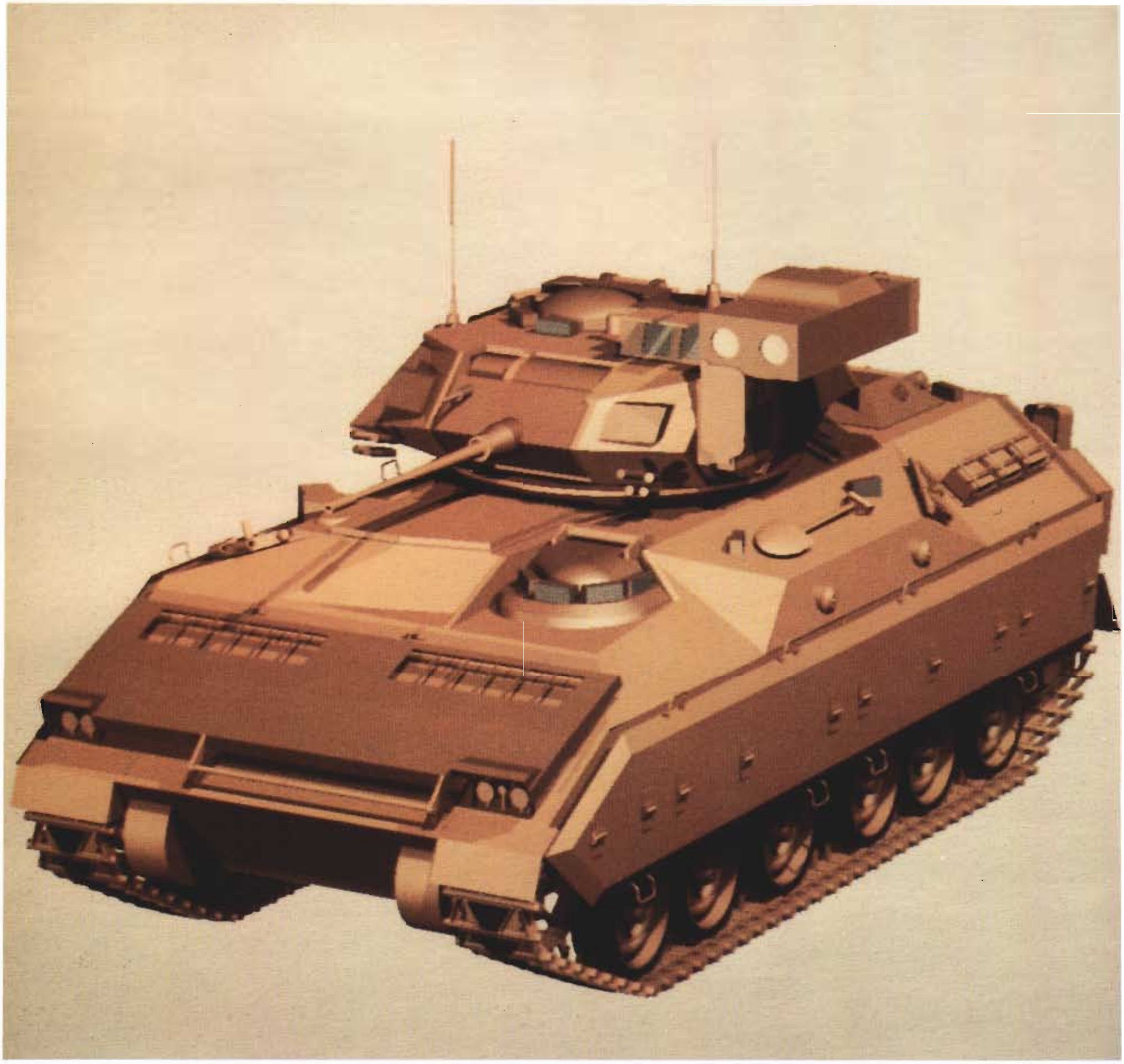


Figure 23. Exterior view of the Bradley Armored Fighting Vehicle.

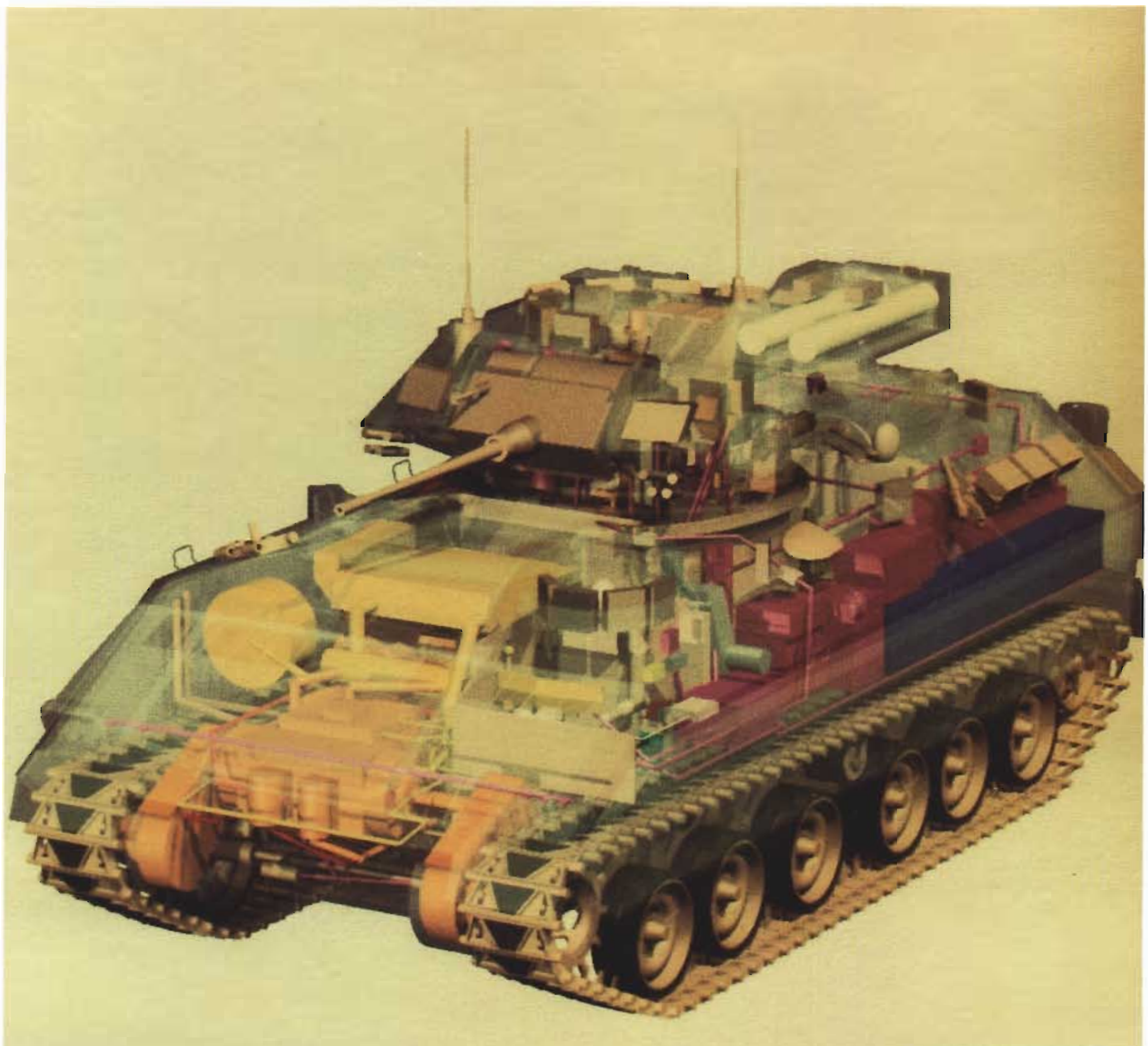


Figure 24. Transparent rendering for the highly detailed Bradley Fighting Vehicle. This is an example of a highly detailed target model illustrative of the evolutionary trend in high-end geometry. This level of model is possible when a system is well-defined and is critical to many advanced prediction codes including Live-Fire vulnerability modeling and vulnerability reduction studies.

than ever that survivability must be pursued *via* a mix of technologies. It is just as clear that we need an analytic environment in which we can bring a] scenario, tactics, doctrine and strategy together with b] mixes of system-performance characteristics in such a way as to point the way to optimal systems design, if not in an absolute sense, at least in a relative way.

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